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Final Report
for the Period
April 1984 to
September 1989

# Current Launch Vehicle Practive and Data Base Assessment

## Volume I: Executive Summary and Report Body

June 1989

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## Foreword

This document represents the final report for Task 8 Propulsion System Reliability Development, of the Research Applications SETA program. The work was performed over the period 30 June 88 to 24 February 1989.

The Air Force Project Officer for this task was Mr. David Perkins, AFAL/VSAB. The SAIC Program Managers were Dr. Robert Long and Mr. William Haynes. The task leader at SAIC was Mr. Joseph R. Fragola. The other principal technical contributors at SAIC were Lewie Booth and Dr. Yu Shen. We appreciate the assistance of Larry Quinn of AFAL in administering this task and Ms. Zun-Yan Wang and Ms. Carol Heymsfield of SAIC in the preparation of this report.

This report has been reviewed and is approved for distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

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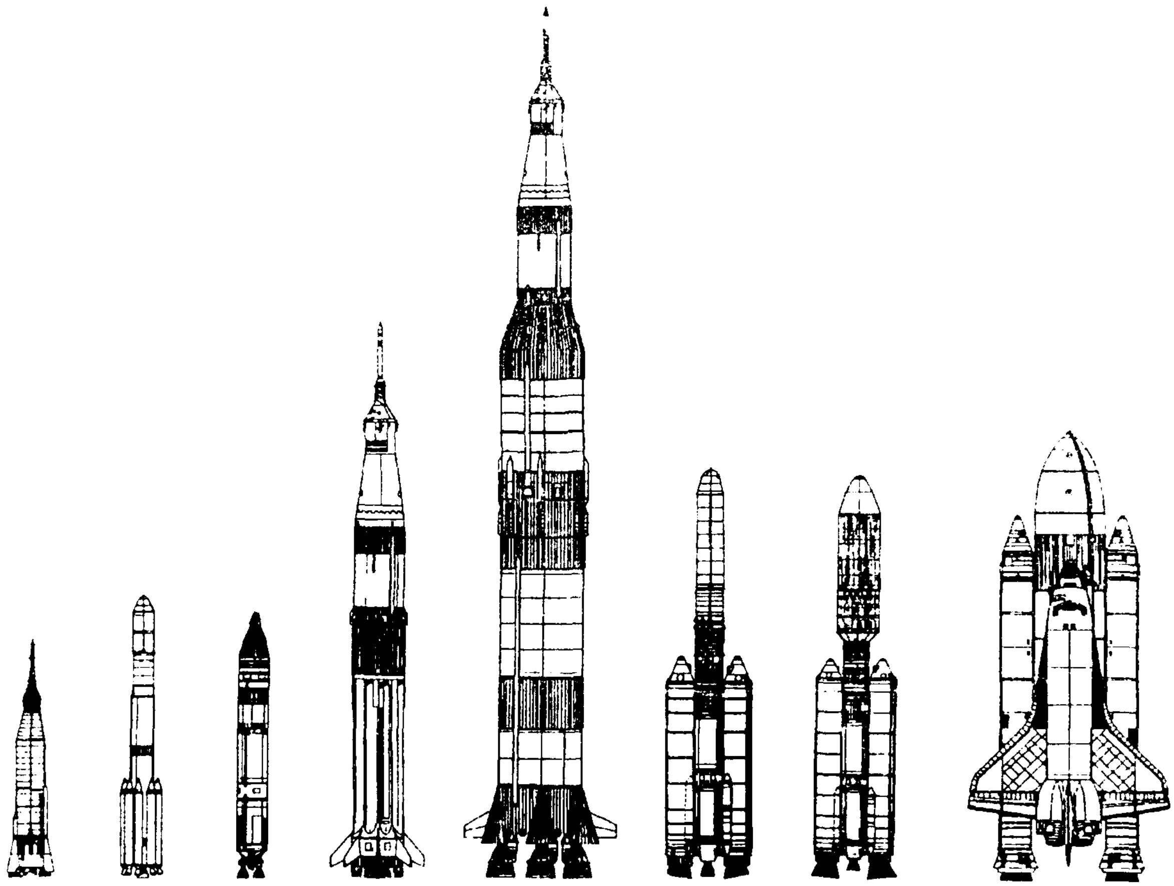
TECHNICAL REPORT (FINAL) / TASK 8

# CURRENT LAUNCH VEHICLE RELIABILITY PRACTICE AND DATA BASE ASSESSMENT

VOLUME I: EXECUTIVE SUMMARY AND REPORT BODY



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reliability, launch vehicle, propulsion development, engine out, failure correlation, variability control, reusability, risk management, reliability performance indicators (PTO), reliability growth analysis.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
This report describes the effort to identify liquid and solid propulsion design parameters, development methodologies, and production/operations techniques related to the improvement of propulsion reliability for future launch vehicles. Six key recommendations are made. There is a section on current practice and data base assessment. This is followed by a section on reliability enhancing methods. Finally, there is a section on quantification and prioritization of methodologies. Volume 1 contains Appendix A which includes an investigation of historical failure correlation factors using the SSME test and flight history as an example, a quick calculation of failure correlation factor versus engine out capability, a reliability analysis of current US launch vehicles, and a hitory of US launch vehicles. Volume 2 contains only Appendix B which is a compendium of trip reports accomplished during the performance of this study.

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APPENDIX A



APPENDIX B (See Volume II)

## EXECUTIVE SUMMARY

The Air Force currently has several ongoing propulsion technology development programs including the significant joint development with NASA of the Advanced Launch System (ALS). Previous investigation by Air Force Astronautics Laboratory and others has indicated that launch vehicle reliability is perhaps the key driving parameter for development program success.

Given the key role played by reliability, AFAL requested that SAIC undertake a study of propulsion system reliability development. The objective of this study was to identify, and where possible quantify and prioritize, propulsion techniques related to launch vehicle reliability.

The study was to include visits to an engine manufacturer, a launch vehicle systems contractor, and NASA sites to develop information to supplement literature searches and independent research to provide a base of information sufficient to allow SAIC to:

- Assess Current Practice and the Resulting Historical Reliability Data Base
- Investigate Potential Reliability Enhancing Methodologies and to
- Quantify and Prioritize the Methodologies

The Study results indicated that current launch vehicle reliability levels are in the order of 90 - 95%. This is substantially below future Air Force system requirements of 99 - 99.9%. Investigation into how these historical levels of reliability could be significantly improved resulted in the development of the following six key recommendations for the consideration of the Air Force and AFAL.

1. Failure correlation factors are key factors of interest to design decision makers. Specific studies, which address what factors have been achieved in the past and what design trades have been made to ensure the low factors quoted by contractors are achievable, appear to be lacking. The Air Force should consider requiring that such studies be undertaken.

2. Variability Control, especially of residual variability, may be the key barrier to high launch reliability achievement. The Air Force should consider requiring that some specific program for variability control be included in future propulsion technology development programs.

3. Reusability has been shown to have indirect, potentially negative, impacts on high reliability achievement. The trade-offs which exist between high reliability and reusability should be clearly identified and included in propulsion programmatic decision making.

4. Risk Management has been shown to have potential benefits in maintaining the high reliability of programs in other industries. The advisability of risk management being included as an integral part of propulsion system development should be considered.

5. Reliability Performance Indicators should be developed whose trend trajectories lead, or presage, the occurrence of reliability problems so that program management action can be taken prior to the development of reliability problems.

6. Reliability Growth Forecasting is important during the development of systems with high reliability requirements. This is especially true when program economics prohibit extensive development test flights. Reliability growth approaches should be investigated and applied as appropriate to propulsion system development programs.

## OBJECTIVE

The objective of this effort was to identify, and where possible quantify and prioritize, liquid and solid propulsion design parameters, development methodologies, and production/operations techniques related to launch vehicle reliability.

## KEY RECOMMENDATIONS

The following areas have been identified as having significant reliability impact. These areas each warrant further in-depth study if the high reliability goals of the Air Force advanced launch vehicle programs are to be achieved in an operational system.

### Failure Correlation*

The percentage of failures which are likely to impact more than one engine in a multi-engine design is of critical design import. This percentage, or "failure correlation factor," must be well below 20% for reliability oriented design approaches such as engine out capability to be effective. The lower the percentage the more effective is this hueristically pleasing design option. Not surprisingly, [illegible] major new engine design characteristics quote extremely low factors (as low as [illegible]%). [illegible] as 1 out of 100 do not seem consistent with other design parameters [illegible] such as high [illegible] pressures) and are considerably lower than factors achieved on recent engine designs (e.g. 17% for the [illegible] main engine test program). Finally, there did not appear to be any significant consideration given [illegible] how these low factors would be achieved in practice.

Recommendation 1 - Failure correlation factors are key reliability parameters to Air Force launch vehicle design decision makers. Specific studies such as parameter design studies which address what factors have been achieved in the past and what design trades have been made to ensure the low factors quoted [illegible] be evident in the reliability designs appear to be lacking. It is recommended that these investigations be made prior to the selection of any design alternative.

### Variability Control

The currently achieved launch vehicle reliability has been shown by this investigation to be below 0.95. However, the investigation uncovered examples of reliabilities in other somewhat similar systems, such as tactical missile systems, which routinely achieve 0.99 and some which approach 0.999. These systems [illegible] operational reliabilities currently meet or exceed the reliability requirements for the Air Force [illegible] launch system have achieved these high reliability levels through the use of intensive variability control programs. While it would be inappropriate to make any direct correlation between tactical missiles [illegible] launch vehicles, it is also clear from a review of the failure data of mature launch systems that the [illegible] to significantly higher reliabilities may be the residual variability [illegible] process. A cursory review of other somewhat [illegible] and gas turbines and recent Air Force variability reduction studies performed as part of the [illegible] program, provide further support for this argument.

Recommendation 2 - Residual variability may be the key barrier to high launch vehicle reliability achievement. For this reason, it is recommended that investigations be made into the effectiveness of [illegible] variability control programs such as Taguchi methods or alternatives. These investigations should

* [illegible] definition cited here is broader than that used traditionally by propulsion system designers. See [illegible] [illegible] of the difference.

be directed at determining the applicability of the methods to the launch vehicle production process. It is further recommended that some specific program for variability control be included throughout all phases of the advanced launch system program.

3. Reusability

Reusability is, on the surface, a design goal of significant program benefit. However, the benefits of reusabiity are significantly compromised if the reliability of an engine is adversely affected by the requirement. Besides the direct costs involved in developing a reusable design, there also appears to be significant indirect costs which are required to maintain reliability in a reusable design. For example, reusability by its very nature tends to decrease the production run. When production runs are decreased, investments in automated production equipment become less economical and the production process therefore tends to become more prototypical. Prototypical production, especially of complex equipment, increases the problems associated with variability control and therefore substantial postproduction testing may be required to ensure high reliabilities. A good example of such an indirect impact on reusability was seen at the Rocketdyne SSME production facility in Canoga Park, California.

Recommendation 3 - Reusability has been shown to have indirect and potentially negative impacts on the achievement of high reliabilities at reasonable cost. The indirect impacts of reusability on reliability and cost through such mechanisms as variability control problems should be thoroughly investigated and the results of this investigation included in the programmatic decision making related to reusability.

4. Risk Management

Achievement of high operational reliabilities in such areas as nuclear power plant safety systems have been significantly supported by a continually active program that attempts to identify the risks to reliable operation and to address them according to their importance. Such a risk management program has been investigated and recommended by NASA SRM & QA for future projects, but it is not clear whether a risk management program is planned for the acquisition of advanced launch systems.

Recommendation 4 - The Air Force should investigate the advisability of incorporating a risk management program as an integral part of any launch system program.

5. Reliability Performance Indicators and Trending

For high reliability programs it is important to identify, early on, symptoms of the process which presage deterioration in performance. This has been done in the financial community, in the commercial aircraft community and in the nuclear power safety community by the development of a set of "leading" performance indicators and developing performance trends based upon the indicator trajectories through time. If such a set of indicators could be developed and trended for advanced propulsion system development programs, the indicator trajectories might provide early warning of problems arising during development and operation. This early warning could provide the time required to institute corrective action before actual program reliability performance is affected.

Recommendation 5 - The Air Force should develop as part of advanced propulsion system development programs a set of potential indicators of programmatic reliability performance. This indicator set should be based originally on historical information, but later updated and validated as advanced propulsion system development programs specific information becomes available.

## Reliability Growth Analysis

In all developmental systems a certain degree of reliability growth is to be expected. However, program managers need to know the pace of the expected growth so that they can determine if the program is likely to meet the operational reliability goals within developmental time constraints. An understanding of the growth process is therefore essential to the determination of the proper role to be played by history in the forecasting of future system reliability. If an historical failure has been analyzed and its cause determined and suitable corrective action is implemented to prevent its recurrence, it is recognized that it would have its probability of occurring again diminished when it is utilized for predicting future performance. But by how much? The determination of how much each failure should be counted is important in order to establish the proper "calibration" for the reliability growth characteristic to be used to determine how well reliability development is proceeding. Several approaches have been developed to address the issue of growth. Among those developed are the early works of Duane at GE, that of David Lloyd of TRW, and that developed by Dr. Yu Shen of SAIC as part of this study. In addition, Bayesian approaches may show promise for improved growth forecasting.

Recommendation 6 - Reliability growth forecasting is important during the development of systems with high reliability requirements such as ALS. Accurate growth forecasts allow program managers to determine early on if reliability requirements are likely to be met. (This is especially important when program economics prohibit extensive development test flights as is [illegible].) Several methods currently exist to allow for forecasts to be generated; however, further development is required to assure that a reasonable growth forecast is developed for advanced propulsion system development programs. It is therefore recommended that the concept of reliability growth be further developed as it applies to advanced propulsion system development programs.

## BACKGROUND

The AFAL currently has several ongoing propulsion technology development programs that are aimed at launch vehicle applications. A fundamental goal for any new launch vehicle is low cost. One element of cost that is receiving increasing levels of national attention is the cost of unreliability. This issue was highlighted by the recent series of catastrophic launch failures. These failures included two Titans, a Delta, an Atlas, and a Shuttle. All were lost in a period of 2 years. Historical data bases indicate that in general, launch vehicle reliability against catastrophic failure is approximately 0.92. This value is dominated by propulsion system failures and is unacceptably low for any future launch vehicles.

The traditional methodologies for the development of propulsion systems have involved the use of traditional manufacturing methodologies coupled with traditional design methodologies that assume some measure of safety factor in the design process. The traditional issue that was fundamental to launch vehicle applications was that the vehicle payload capability was highly sensitive to the mass properties. Hence, margins were decreased to the maximum extent possible during the design phase. There remains a distinct development transition to flight weight hardware in most aerospace developments. Reliability was only subsequently evaluated as a secondary concern. Point estimate techniques for estimating application reliability were employed rather than rigorous statistical testing. Manufacturing process control was instituted after development in order to qualify vehicles for manned flight or higher confidence of success following catastrophic failures. It is apparent that in order to achieve higher levels of reliability in propulsion systems, and hence in the launch vehicles, alternative development approaches need to be explored.

There have been several suggested approaches to achieving higher reliability. Design for reliability philosophies include redundancy techniques and higher design margins. Process control advocates point to human error contributions to failure and article to article variations, proposing that more automated production and higher levels of quality control and non-destructive testing will achieve desired reliability. It is fundamentally assumed that design engineers should be more aware of ultimate reliability and producibility issues as they pursue designs. Inevitably, the greatest stumbling block to achieving higher reliability goals is limited funding available for development and qualification programs and the historical reliability approach perspective, which consigns probablistic techniques to only the top most levels of program analysis and evaluation. While history has shown it to be true that in the ultimate design reliability not only costs nothing but will produce significant cost benefits, this is not true in the near term design development phase. Here reliability tasks increase, at least initially, the cost and they do so in an environment where funding is scarce and where reliability needs must compete with other more visible programmatic needs (such as performance upgrades). In such an environment of new program development within strict resource constraints reliability resources can be eroded in favor of programmatic needs considered more immediate unless investments in reliability are "fenced in" early and not confused with management reserves.

# 1.0 (TASK 1) CURRENT PRACTICE AND DATA BASE ASSESSMENT

## 1.1 Current Practice

### 1.1.1 Current Practice Background

Corporations involved in the design, manufacture, test and operation of propulsion systems generally have infrastructures that result from specific government agency requirements. Those controls which exist within any given infrastructure that have an impact on reliability also exist largely due to government requirements. At the highest level these controls consist primarily of Failure Modes and Effects Analysis (FMEAs) and Problem (or Failure) Reporting and Corrective Action Systems ( PRACAs/FRACAs). Although these controls have had a positive impact on reliability the impact, because it is often somewhat indirect, is not readily measurable. Thus, it is difficult to ascertain quantitatively that spending a given amount of resources on FMEAs or PRACAs will in fact pay off. In addition, there are, at least in the initial phases of program development, few financial incentives for "better" reliability even though the costs of failure dictate substantial down stream benefits from investing in reliability. Furthermore, even if there were reliability incentives, it would be difficult for manufacturers to know where to spend their scarce resources to obtain the best reliability returns. This is primarily due to inconsistent or non-existent reliability data bases.

The problem is further compounded by the constraint of sample size on the measurement of achieved reliability in highly reliable systems. In other words, to demonstrate that a given reliability has been achieved at a reasonable confidence level, a large number of systems must be tested. It is obvious that in most cases this approach is not practical from a cost/schedule standpoint. This is not to say that presently attained reliabilities are inadequate to satisfy the previously and currently existing requirements. In fact, the attained reliability of any propulsion system is generally based on relatively small sample sizes and the underlying assumption that each propulsion system firing is independent of all others. This simply means that while we may not know precisely (from a reliability standpoint) where we are now, we do know where we are well enough to understand that we are far from the high reliability goals desired of future propulsion systems.

However, the relevant question is not where we are now, but how can an improvement in reliability be achieved? Because of the relative nature of this question, it may turn out that accurately predicting reliability improvements is easier than measuring attained reliability.

### 1.1.2 Major Activities Constituting Infrastructures

Due to funding limitations it was not possible to revisit manufacturers in order to benefit from the total information obtained from the initial visit. The revisits would have concentrated not just on design, manufacturing and test, but on transportation and storage as well.

The second visits would be used to form a clearer picture of the detailed approaches taken by liquid and solid manufacturers.

However, based on the initial visits taken, six major activities have been identified in the life cycle of a propulsion system: design, manufacturing, test, transportation, storage, and operation. The infrastructure that has evolved has centered on design, manufacturing and test. Activities related to transportation, storage and operation tend to be restricted to problem correction rather than a planned strategy to anticipate problems.

Design - The Design activity primarily involves the creation of a system that meets the specified requirements of a contract. Typically a design is generated and goes through a design review process usually consisting of preliminary, critical, and final design reviews. The review of reliability requirement achievement during these reviews is currently based (because of the lack of a detailed historical data base for propulsion systems), upon the manufacturer's engineering judgement or on qualitative review of design specific failure modes whose elimination or mitigation is again based upon manufacturer's recommendations which are judgementally based and therefore difficult to objectively assess as to their probability of being successfully achieved in the implemented design.

Manufacturing - Once the transition is made from design to manufacturing, the activities focus on how to best minimize the manpower and materials required to produce the system while satisfying quality control constraints. Manufacturing procedures and flow diagrams are the primary mechanisms for this activity. Quality Control plans mutually prescribed by clients, primes and major subcontractors are also imposed.

Test - Testing activities primarily involve qualification and feasibility testing. They are primarily intended to test the functional adequacy or the potential of a given design implementation. In this way they can clearly indicate that a propulsion system performance specification such as thrust to weight ratio, a specific impulse has not been achieved, but they only indirectly indicate lack of reliability achievement. This is especially true of new designs. These tests do not usually involve enough test time (or numbers of systems) to produce a statistically significant indication of system reliability capability. When failures do occur, they may have been induced by consciously over extending the design limits. In fact, the tests may be conducted to determine design weaknesses through test failure so that the failures can be examined and corrective action taken to improve the design. These tests therefore may not always provide useful information concerning the assessment of system reliability capability although they certainly do produce information useful to reliability improvement.

Transportation - Transportation activities can have obvious negative impacts on reliability due to the influence of shock, vibration, humidity, and thermal transients. These and other environmental factors can act independently or synergistically to decrease reliability. Controls are in place dictating packaging and handling requirements primarily through specifications. Unfortunately, not all problem (or failure) reporting and corrective action systems feedback problems that occur because of inadequate package and handling requirements. Such a closed loop system would provide a mechanism for rewriting of specifications.

Storage - Like transportation, storage activities can also have a negative impact on reliability. This is true not only from the standpoint of environmental conditions, but storage time as well. When rocket booster dependent programs experience a delay, then all limited life items become factors affecting reliability.

Operation - The operating time for booster rockets is a matter of a few hundred seconds with the proviso that some of the rocket engines or solid booster casings are reusable. Achieved reliability is measured classically by using operating data and applying statistical distributions such as the binomial. As with the testing activity, when failures occur, the devices are reexamined and corrective action is initiated followed by retest. Since the corrective action taken obviously is intended to eliminate failure mechanisms and thereby improve reliability, it is difficult, if not impossible, to use a classical approach to measure reliability achievement in developmental systems with high reliability goals and limited operating histories.

### 1.1.3 Current Infrastructure Activities Affecting Reliability

Although there are some specific differences between prime contractors and major subcontractors, in general the controls affecting reliability which are the responsibility of the reliability discipline are Reliability Predictions, Failure Modes and Effect Analysis (FMEAs) and Failure Reporting and Corrective Action systems (FRACAs). The quality control discipline has a direct impact on reliability but is not formally a part of the reliability discipline. "Lessons Learned" is often a semi-formal approach to reliability improvement and when used, it is as likely to be found in the design group as the reliability group.

Only the FRACA system provides a closed loop means of correcting problems. In their present form, FRACAs are not structured to quantify reliability or to become a proactive part of measured (quantified) reliability enhancement.

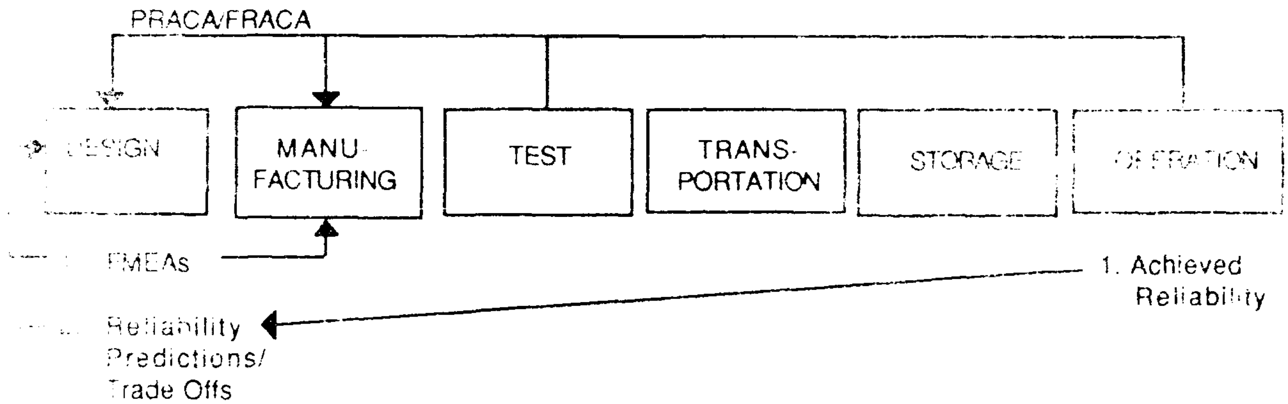



Figure 1. Existing infrastructure controls intended to enhance reliability.

Figure 1 illustrates the six infrastructure activities as they relate to reliability activities. The most commonly used reliability activities are:

- FMEAs
- Reliability Predictions/Trade-offs
- PRACA/FRACA Systems
- Measurement of Achieved Reliability

What FMEAs are and how they are used is described in the following section under "Reliability Engineering Analysis". Reliability Predictions/Trade-offs are also discussed in the same section under the heading of "Quantitative Reliability Engineering Design Tools" along with other tools that are available to reliability engineers. Figure 2 contains a comprehensive list of reliability Tools and Techniques. PRACA/FRACA Systems are discussed in detail in Section 1.1.3.2.

Measurement of Achieved Reliability due to its complexity is treated separately in Section 2.2, "Historical Data Analysis (Reliability Growth)" and in Appendix A.3. "Reliability Analysis of Current US Launch Vehicles".

The purpose of Figure 1 is to illustrate the limited use of presently available reliability engineering techniques and tools as well as the limited use of information from activities such as transportation and storage.

It is clear, based on the information gathered to date, that no single company has utilized all the tools and techniques available to reliability engineers on any given project nor has the information from transportation and storage been fully utilized. The fact that all the resources of reliability technology have not been utilized is not a result of negligence on the part of manufacturers. Often they may not be provided with specific requirements to address all these issues by their government customers and are not normally funded to conduct these types of analyses.

Although not directly related to launch vehicle reliability, a recent example of how the storage activity can affect reliability is given by the recently launched TDRSS spacecraft. After the Challenger accident the spacecraft spent an extra 2 1/2 years on the ground. Deterioration was suspected in the bolt cutter ordinance and for this reason a reliability study was conducted by the contractor. The study resulted in the determination that the bolt cutters required replacement. The successful launch of TDRSS is now a matter of record. Total credit for this success cannot be taken by the individuals involved in this reliability analysis, but a significant contribution was made to this success as a result of diligent ordinance and reliability engineers taking the initiative and going beyond typical practice. The only way to make such protection "routine" is to expand current reliability practice so as to create an infrastructure such as the one depicted on Figure 8 in Section 2.3.

Reliability Engineering Analysis - There are a number of tasks that are specifically related to reliability as shown in Figure 2. It is not the purpose of this report to fully describe each technique and design tool but to highlight those most commonly used in the rocket industry. The two most commonly used methods for reliability analysis are:

- Failure Modes and Effects Analysis (FMEA) or Failure Modes, Effects and Criticality Analysis (FMECA).
- Quantitative Reliability Engineering Design Tools such as predictions or Trade-offs.

Failure Modes and Effects Analysis is a "bottom up" method intended to identify, classify and document failure modes and their effects as well as possible corrective actions or compensating or mitigating provisions.

The purpose of an FMEA is to:

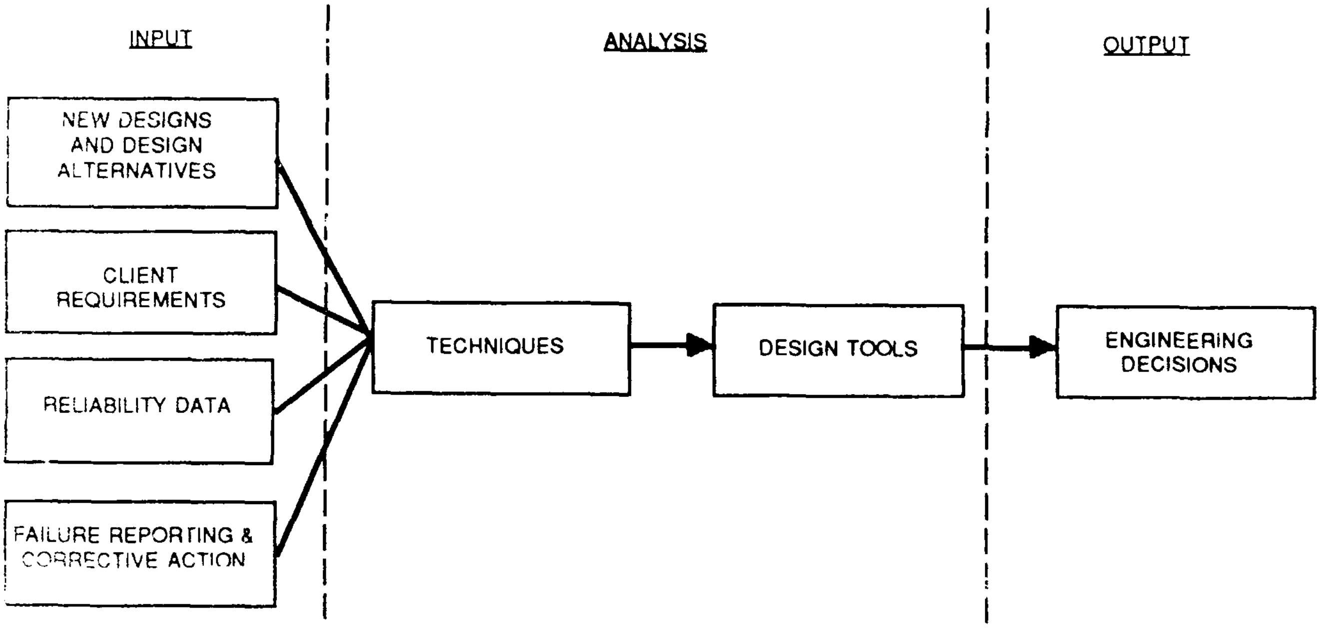
1. Assist in selecting design alternatives with high reliability and high safety potential during early design phase.

2. Ensure that all conceivable failure modes and their effects on operational success of the system have been considered.

3. List potential failures and identify the magnitude of their effects.

4. Develop early criteria for test planning and the design of the test and checkout systems.

5. Provide a basis for quantitative reliability and availability analyses.




**TECHNIQUES**

1. QUANTITATIVE ANALYSIS
   - FORMATS-RELIABILITY GRAPHS RELIABILITY BLOCK DIAGRAMS, FAULT TREE DIAGRAMS, MARKOV TRANSITION DIAGRAMS, DECISION TREES, TRUTH TABLES, DIGRAPHS
   - ANALYTICAL METHODS-BOOLEAN ALGEBRA, MARKOV MATRIX ALGEBRA, EVENT SPACE ANALYSIS, MINIMUM CUT SETS, TIE SETS, MONTE CARLO SIMULATION, PATH TRACING, DECOMPOSITION
2. QUALITATIVE ANALYSIS
   - FORMATS-FMEA'S, CRITICAL ITEMS LIST, FAULT TREE DIAGRAMS
   - ANALYTICAL METHODS-FAILURE ANALYSIS, ROOT CAUSE, COMMON CAUSE, CRITICALITY RANKING

**DESIGN TOOLS**

1. COMPARATIVE ANALYSIS
   - ENGR. TRADE OFF'S
   - SENSITIVITY
   - OPTIMIZATION STUDIES
2. ABSOLUTE ANALYSIS
   - APPORTIONMENT
   - PREDICTION/MEASUREMENT OF ACHIEVED RELIABILITY

**ENGINEERING DECISIONS**

1. RECOMMEND DESIGN ALTERNATIVES
2. MAINTANINABILITY RECOMMENDATIONS
3. PREVENTIVE MAINTENANCE PROGRAMS
4. SPARE PARTS PROVISIONS
5. RECOMMENDED TEST INTERVALS

Figure 2. Reliability engineering tasks typically used in design

6. Provide historical documentation for future reference to and in analysis of field failures and consideration of design changes.

7. Provide input data for tradeoff studies.

8. Provide a basis for establishing corrective action priorities.

9. Assist in the objective evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics and automatic and manual override.

When considering reliability analysis of a design, one usually thinks of all the analytical steps leading to an estimate of the reliability of a given item. A complete analysis requires comprehensive input data that include material properties, design details and component failure rates; however, it is not necessary to wait until all of these are known before much can be determined about the reliability of the design.

Failure Mode Effects and Criticality Analysis (FMECA), is essentially similar to a Failure Mode and Effects Analysis but in this case the criticality of the failure is analyzed in greater detail (and may in some instances be quantitatively evaluated) and assurances and controls are described for limiting the likelihood of such failure. The four fundamental facets of such an approach are (1) Failure Identification; (2) Potential Effects of the Failure; (3) Existing or Projected Compensation and/or Control; and (4) Summary of Findings.

The most hazardous pitfall is the potential of mistaking form for substance. If the project becomes simply a matter of filling out the FMEA forms instead of conducting a proper analysis, the exercise will be ineffective. For this reason, it might be better for the analyst not to restrict himself to any prepared formalism. Another point: if the system is at all complex, it is risky for a single analyst to imagine that he alone can conduct a correct and comprehensive survey of all system failures and their effects on the system. When applied to complicated systems, these techniques call for a well coordinated team approach.

Comparative Analysis and Absolute Analysis are the two general types of quantitative reliability engineering design tools.

Comparative Analysis - When alternative designs for achieving given (or desired) levels of reliability are under consideration, characteristics for each design are expressed quantitatively as a means of comparing the relative reliability of each design alternative. For this particular type of analysis, failure and repair data need not be exact since the purpose is to compare alternatives rather than to obtain estimates of absolute values.

There are three types of comparative analysis commonly undertaken:

- Trade-offs
- Sensitivity Studies
- Optimization Studies

Trade-offs, among various design alternatives, are conducted so that the alternatives with the best Benefit to Cost Ratio may be selected. The Benefit/Cost Ration is determined by incorporating the effects of reliability factors, installation and operating costs, degraded modes of operation, etc. Trade-offs involve achieving the proper balance among reliability, performance, and cost.

Sensitivity analysis involves the variation of input parameters to mathematical models in order to assess the relative effect of component characteristics and data accuracy on a given system's reliability. The results are used to identify areas where improvement in design will have the greatest potential impact on reliability.

Optimization studies carry the concept of sensitivity analysis one step further by varying the input parameters until a set which appears best from a reliability perspective within the system constraints is obtained.

Absolute Analysis involves the use of numerical results of an analysis in an absolute sense (Design A has a reliability of 0.90"). It results in a "stand alone" number, not a "relative comparison" type number.

The two types of absolute analysis are:

- Apportionment
- Prediction

Apportionment is used when a specific level of reliability is prescribed. For instance, a client may prescribe a certain percent increase in the reliability of an existing propulsion system. The procedure (greatly simplified) is:

1. Apportion the reliability of the system to each subsystem based on past performance.

2. Identify those subsystems which have the least desirable reliability performance. Include all factors which affect this performance such as random failures, common cause failures, distribution of downtimes, human reliability, etc.

3. Determine what corrective measures may be taken to increase the reliability of each subsystem.

Prediction requires utilizing mathematical models, input data, and probability theory for predicting reliability, taking design actions based upon the predictions, measuring (or gaining new knowledge)and then repredicting, and acting again or remeasuring continually throughout a program of development or use.

Reporting and Corrective Action Systems - "Failure Reporting and Corrective Action": (FRACA) as well as "Problem Reporting and Corrective Action" (PRACA) are the two types of reporting and corrective action systems that presently exist in the rocket industry. The FRACA system is required by the Air Force and the PRACA system is required by NASA. Although these two systems may differ in minor detail, the intent of the requirements and methods used by manufacturers to carry them out is very similar. The following [illegible] from a typical manufacturer.

Company XYZ maintains a closed-loop failure reporting and corrective action system to ensure investigation of the cause of failures and to provide appropriate corrective action and failure recurrence control. The FRACAs place emphasis on analysis of failure data to provide early detection of defects. Subsequent investigation and corrective action attempts to find and correct failure causes early in the build cycle in order to minimize costs associated with higher level failures.

FRACAs incorporate the following features:

1. Use of a failure report form which provides a failure description, analysis and corrective action, as well as basic information including: hardware name; operational level, type and environment; hardware identification number; date of failure; name of responsible unit engineer and failure reporting engineer.

2. A project failure reporting procedure or RAM program plan section which defines:

- The level at which failure reporting begins.

- The types of anomalies for which failure reports will and will not be written.

- The flow of hardware and paperwork associated with failure analysis.

- The responsibilities of the R&M and QA organizations.

3. The completed failure reports incorporate the corrective action implemented both immediately (e.g., part removed and replaced) and long term (e.g., engineering order to implement design change).

4. Every failure report requires a close out.

5. The program/project maintains a current list of all failures and the status of those failures.

Basic terminology used in FRACAs is as follows:

1. TRS - Test Record Sheet - Running log of spacecraft area test events; initiated by test inspector.

2. SQUAWK (Log)- Narrative which records spacecraft or space propulsion system area assembly and test problems; initiated by test inspector.

3. TDR - Test Discrepancy Report - Records test failures at various levels of assembly and test; initiated by test inspector.

4. TRF - Test Failure Report Records the problem descriptions, failure analyses, and corrective actions; initiated by reliability engineer.

5. RAR - Reliability Analysis Report - Computerized output of combined information from TDR and TFR.

6. FRB - Failure Review Board - Joint meeting of Contractor/Customer personnel to review and closeout failure.

<u>Sequence of Activities</u> - A typical flow of failure reporting paperwork and the associated hardware is shown in Figure 3.

Although FRACA/PRACA systems are intended to be a "cradle to grave" system, manufacturers tend to emphasize manufacturing (using Q.C. as the control and corrective action system) and test (using the process of Figure 3 as a corrective action system). This is primarily because these are the two areas over which they have complete control. Feedback from the customer (except, of course, for catastrophic failures) is often inconsistent.

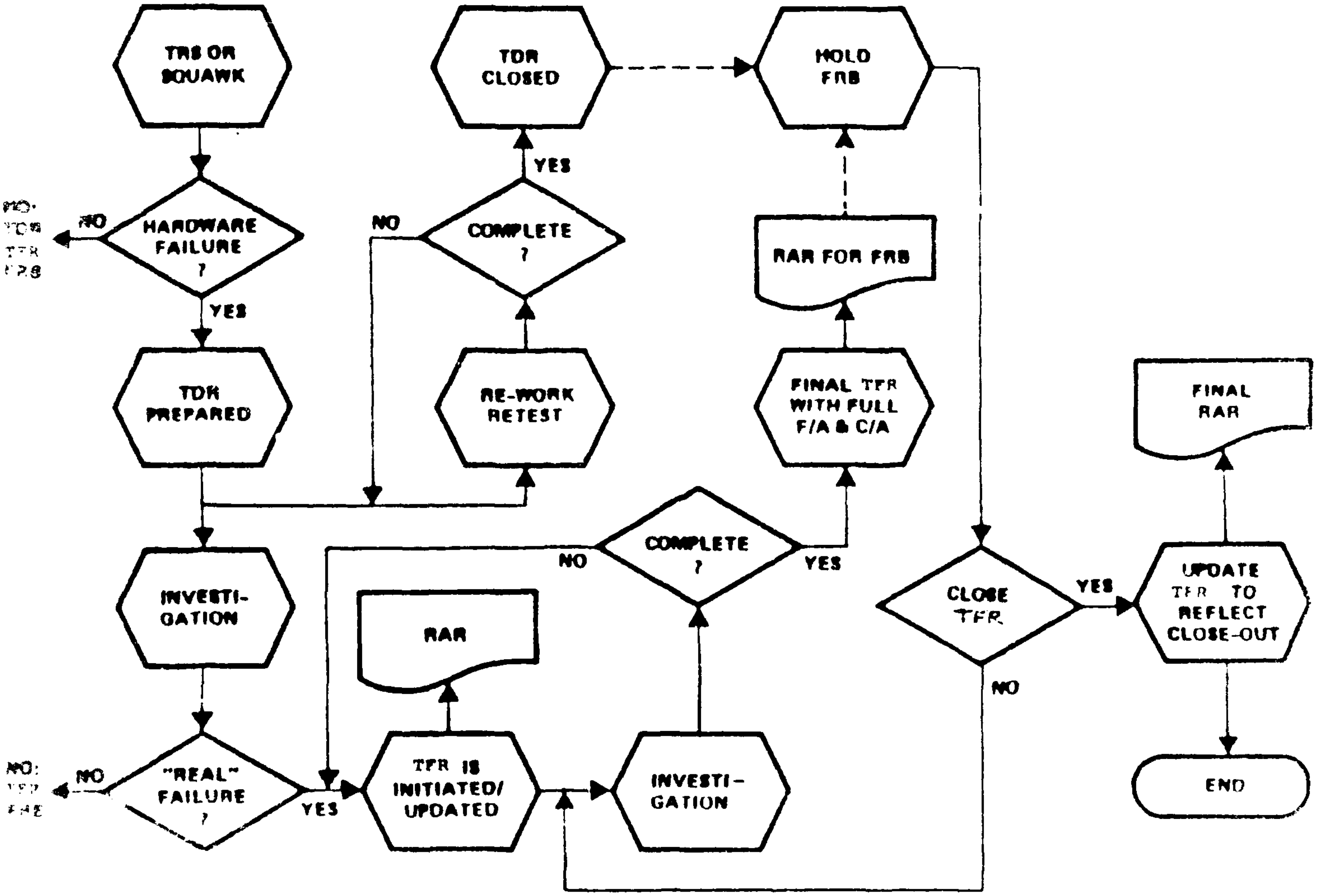



Figure 3. TDR/TFR/RAR paper flow.

For example, if a failure occurs and the equipment is pulled for repair, the paper work often does not state why the equipment failed. In the case of the SSME, a recent review of non-conference reports (UCRs) indicated that only 20% were included in the NASA PRACA system according to one contractor. 80% were excluded by the reporting requirements. These requirements are intended to limit the reporting to serious problems and to prevent the system from becoming overwhelmed by problems of a minor nature. Such a system serves well to aid in serious problem tracking and close out, but can sometimes eliminate the detailed background information required for definitive problem analysis and root cause determination. In the case of the SSME, such investigations required use of the UCRs combined with the contractor's (Rocketdyne) in house problem tracking systems. Thus, the problem is two-fold: not all problems are reported and those that are reported are not always adequately described.

Comments - Failure reporting is most effective when viewed as an engineering activity rather than as a bookkeeping function. Opportunities exist for failure reporting personnel to enhance screening effectiveness, identify potential trends, and to minimize costly downstream anomalies. Increased computerization of FRACAs allows for rapid information dissemination and less time spent on routine paperwork tasks, as long as increased use of computers must not be made by sacrificing detailed problem descriptions.

The FRACAs begin with procurement and continue through receiving inspection manufacturing, test, launch-site activities and mission operation. Control of discrepancies found in receiving and in-process inspection, all non-test discrepancies and Material Review Board (MRB) activities are primarily the responsibility of Quality Assurance and are described in the Quality Assurance Program Plan. Reporting of parts and materials problems (including Alerts, etc.) is the responsibility of Parts, Materials and Processes (PM&P) personnel. Test discrepancy control is primarily the responsibility of the reliability organization. In the course of performing this function, a reliability engineer may encounter conflicting priorities within the project in assuring that proper failure analysis and corrective action occur in response to test discrepancies. Examples include:

1. Manufacturing personnel want units repaired and out of their hands.

2. System Integration personnel want units back into stores or back into their hands.

3. The unit engineer wants a test discrepancy to be due to a manufacturing defect or a parts problem, and he may now, due to the passage of time, be assigned to a new project.

4. The project manager doesn't want to spend any more money on the situation.

5. The project engineer believes whatever the unit engineer tells him.

6. The system engineer is worrying about link performance or something of the sort.

In the face of these conflicts, the reliability engineer's objectives must prevail. The Failure Review Board exists to help assure that each failure is properly closed out. Satisfactory closeout of a failure will occur when:

1. A failed unit is fixed and has passed the test which it failed.

2. The probability of the problem recurring in the unit is negligibly small.

3. The problem has been shown not to exist in any other unit.

A computer system is often used to record and track test discrepancies from the time of occurrence through Failure Review Board closeout and beyond. The computerized system provides:

1. A reporting vehicle for alerting Quality Assurance, Reliability, Engineering, Manufacturing, Test and Program Management of failures and need for action.

2. A permanent record of the cause, significance, effect, and corrective action for each failure.

3. A vehicle for requesting remedial action of the procurement, design, manufacturing, test and handling organizations.

4. A retrieval system for identifying failure trends, providing status summaries and locating historical failure information.

While PRACAs/FRACAs perform well in the failure tracking and problem close out system mode for which they were intended, they were not designed to be reliablity data bases even though they may contain information considered for this latter purpose. It should therefore not be surprising that PRACAs often lack the information required for reliability analysis and prediction. The reasons for this vary but the primary reason is as follows. PRACAs are intended primarily to keep reliability management and program management informed that serious problems have been identified and are being attended to. Including minor problems or supplemental information which is not critical to management tracking (such as the part exposure time at failure) may overload management and therefore this information is screened out of the system by the reporting requirements. While this may be desired from a problem tracking standpoint, it eliminates the precursor information essential to a reliability data base. For example, the SSME PRACA system only includes 20% of the UCR information which would be required for a reliability data base and it includes almost no exposure at time of failure information.

## 1.2 Data Base (Historical)

### 1.2.1 Data Collection

The objective of this subtask was to collect the material necessary to understand the present state of design, the current manufacturing techniques and the operational parameters of solid and liquid propulsion rockets. Collection methods included visits to NASA and Air Force sites responsible for solid and liquid propulsion rockets. Collection methods also included visits to the sites of rocket manufacturers and users and access to in-house publications, technical and public libraries for text books, reports and articles on rockets.

Trip reports (see Volume II: Appendix B) documented the names of contacts made, insights gained through formal or informal question and answer sessions with these contacts, the type of information collected (hard copy reports, historical data sets and for which rockets and time frames) and the type of process viewed during facility tours (production, maintenance, design). Information gathering focused on the retrieval of sets of historical rocket launch and test performance data, textbook discussions of the physical attributes of solid and liquid rockets and subtypes, and studies conducted to evaluate design and performance tolerances of individual or collective rocket performance parameters. The output of this task was a set of rocket characteristic and performance data.

### 1.2.2 Data Organization

The data gathered from the site visits and the information collection process described above was organized to facilitate its use. For hardcopy material and site trip reports, a filing system was constructed,

separating solid from liquid rocket data, then categorizing by rocket use (booster, strap-on, Orbit Adjust, Payload Assist Module), followed by sorts on fuel type and rocket type. The Data Summary Sheets that follow were constructed to allow at-a-glance review of the data available on the various rocket types in these rocket use and fuel type categories. Historical data on rocket test/launch were organized by entering it into a computerized data base system, DBase III+, when the data was available, to allow data to be more easily stored and sorted.

### 1.2.3 Representative Design Parameter Development

Using the information gathered and organized, a candidate design configuration was selected for solid and liquid rockets as a baseline case. This baseline was used to establish a structure of rocket mission and performance characteristics which also define a structure for data entry and storage. The rocket mission data vector, or the column headings for a data table, reflects data categories from historical performance sets, such as data of test/launch, success or failure, rocket designation (name, production lot), and type of mission (R&D, space Mission). Rocket performance vector entries were determined by the technical literature search and site visit discussions citing rocket attributes such a fuel, oxidizer, thrust and diameter. The baseline structure which these vectors constitute was expanded and defined further as more insight was gained into the characteristics which drive rocket reliability.

Following the Data Summary Sheets is a matrix containing the reliability of U.S. launch vehicle failures, tabulated in Table 1 and 1a-1f. The details of how this matrix was generated are contained in Appendix A 3.

## 1.3 Deficiencies of Current Aerospace Reliability Practice In Application to Current Advanced Launch System Needs

Current Aerospace Reliability practice has not been able to affect the high reliabilities specified for Air Force advanced launch systems. Current practice, as it seems from the investigations undertaken as part of this effort, is relevant toward the production of launch vehicle systems whose range of achieved reliability is upper bounded at 95%, and these levels have been achieved only after significant development programs over which significantly lower reliabilities were the norm (80% - 90%). Many of the deficiencies in current practice are a product of the developmental history of aerospace reliability technology and its resulting evolution rather than direct misapplications of reliability techniques. It has taken almost 30 years for a systematic reliability discipline to be developed since its early beginnings in the Titan and Apollo programs. At the time of its creation, the US and world industrial base was quite different. Failures of small electronic components because of their use in great numbers in complex aerospace designs had a tendency to defeat the best efforts of system designers and render embarrassingly useless, expensively developed systems. In the case of early launch vehicles, national prestige and credibility of ICBM deterence required that these problems be eliminated quickly. The electronic systems were the roots of aerospace reliability, especially in the era when quantitative information was completely unavailable (if not unheard of).This tended to influence reliability technology development toward the generation of techniques which could help quickly to improve the performance of systems without undertaking the long term development of more reliable individual devices. Papers which touted the development of reliable systems from less reliable devices, the initiation of qualitative investigatory techniques such as FMEAs, and the use of redundancy to shore up the areas of weakness graduated from the academic classroom of the 50's and early 60's to become the industrial practice of the late 60's and early 70's. Finally, they became institutionalized in the late 70's and 1980's.

While exposure of component functional failure effects through FMEAs and their elimination through redundancy works, and works well for electronic systems where weight and operational constraints are minimized and the effect of a single failure is to some degree localized, the usefulness of this approach has always been limited in propulsion systems. In fact, the use of this currently institutionalized qualitative

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# DATA SUMMARY SHEET



| ENGINE or MOTOR NAME | MOTOR 1 UA 1205 | MOTOR 2 UA 1207 | MOTOR 3 THIOKOL TX526-2 | MOTOR 4 THIOKOL TX-780 | MOTOR 5 THIOKOL STAR 48 |
|---|---|---|---|---|---|
| Agency | USAF, Commercial | USAF | NASA | USAF | NASA |
| Manufacturer | UTC | UTC | Thiokol | Thiokol | Thiokol |
| Designation (stage or motor) | | | Castor 4 | Castor 4A | PAM-D |
| Engine or Motor weight (lb) | | | 3,222 | | 400 |
| Propellant weight (lb) | 232,000 | | 20,556 | | 4,400 |
| Stage number | 0 | 0 | 1 | 1 | 3 |
| Oxidizer/Fuel | solid | solid | solid | solid | solid |
| Mixture ratio (O/F) | | | | | |
| Coolant | | | | | |
| Length/Diameter (ft)/(ft) | 90.4/10.2 | 112.9/10.2 | 36.6/3.3 | 36.6/3.3 | 7.[illegible] |
| Thrust (sea lev) (lb) * lb-sec | 123,144,000* | 159,700,000* | 83,640 | 97,556 | |
| Thrust (vacuum) (lb) | | | 92,400 | | 15,000 |
| Chamber pressure (psia) | | | 540 | | 570 |
| Spec impuls (sea level) | | | 230 | | |
| Spec. impuls (vacuum) (sec) | | | 256 | | 293 |
| Total burn time (sec) | | | 56 | | 85.3 |
| Nozzle expansion ratio | | | 8.0 | | 54.9 |
| Nozzle exit area (ft·ft) | | | 6.1 | | 4.75 |
| Engine cant angle (deg) | | | 11 | | 0 |
| ... material | | | | | |
| ... segment number | | | | | |
| ... | | | | | Spin Stabilized |
| Thrust Coeffiecnt Cf | | | 1.411 | | 2.1 |
| Nozzle discharge coefficent Cd g | | | 6.13E-3 | | 7.2E-3 |
| Engine cycle | | | | | |
| Mass Discharge Rate (lb/sec) | | | 363.7 | | 51.2 |
| Engine cost | | | | | |
| 28 Engine Reliability | 0.9975 | | 0.9993 | | 0.9769 |
| Vehicle Name | Titan 34D, Titan 3 | Titan 4 C.G.P., Titan 4 IUS | Delta 3914/3924, 3910/3920/PAM-D | Delta 6925 | Delta 3910/PAM-D, 3920/PAM-D |

| NUM | ENGINE or MOTOR NAME | MOTOR 6 THIOKOL 48B | MOTOR 7 HERCULES GEM | MOTOR 8 SPACE SRB | MOTOR 9 THIOKOL TE364-4 | MOTOR 10 UTC ALGO 3 |
|---|---|---|---|---|---|---|
| 1 | User Agency | USAF | USAF | NASA | NASA | NASA,USAF |
| 2 | Manufacturer | Thiokol | McD/Douglas | | Thiokol | UTC |
| 3 | Designation (stage or motor) | PAM-D | Gr-Ep Motor (GEM) | | TE-M-364-4 | Algol 3A |
| 4 | Engine or Motor weight (lb) | | | 285,000 | 200 | 4,000 |
| 5 | Propellant weight (lb) | | | 1,115,000 | 2,300 | 28,000 |
| 6 | Stage number | 3 | 1 | 1 | 3 | 1 |
| 7 | Oxidizer/Fuel | solid | solid | Aluminum powder/ Ammonium perchlorate | solid | solid |
| 8 | Mixture ratio (O/F) | | | 4.4 | | |
| 9 | [illegible] | | | | | |
| 10 | Length/Diameter (ft)/(ft) | 7.2/4.0 | 36.6/3.3 | 149.0/12.0 | 6.8/3.2 | 30.8/3.74 |
| 11 | Thrust(sea lev) (lb) * = lb.sec | | 94,556 | 2,650,000 | | 93,250 |
| 12 | Thrust (vacuum) (lb) | 15,000 | | | 14,800 | 105,112 |
| 13 | Chamber pressure (psia) | | | | 550 | 450 |
| 14 | Spec. impuls (sea level) | | | | | 229 |
| 15 | Spec. impuls (vacuum) (sec) | | | | 283 | 259 |
| 16 | Total burn time (sec) | | | 120 | 44 | 56.11 |
| 17 | Nozzle expansion ratio | | | | 33 | 6.48 |
| 18 | Nozzle exit area (ftxft) | | | | 3.14 | 5.67 |
| 19 | Engine cant angle (deg) | | | | 0 | 0 |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | | | | Spin Stabilized | Aerodynamic Fins and Jet Vanes |
| 23 | Thrust Coeffiecnt Cf | | | | 1.96 | 1.645 |
| 24 | Nozzle discharge coefficent Cd g | | | | 6.94E-3 | 7.18E-3 |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | | | | 52.3 | 407.2 |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | | | 0.9813 | 0.9769 | |
| 29 | Vehicle Name | Delta 6925/7925 | Delta 7925 | Space shuttle | Delta 3914/3924 | Scout Launch Vehicle (SLV) |

| NUM ENGINE or MOTOR NAME | MOTOR 11 THIOKOL TX354-3 | MOTOR 12 THIOKOL TE-M-762 | MOTOR 13 THIOKOL TE-M-640 | MOTOR 14 THIOKOL TE-M-364-4 | MOTOR 15 THIOKOL TE-M-616 |
|---|---|---|---|---|---|
| 1 User Agency | NASA,USAF | NASA,USAF | NASA,USAF | USAF | USAF |
| 2 Manufacturer | Thiokol | Thiokol | Thiokol | Thiokol | Thiokol |
| 3 Designation (stage or motor) | Castor 2A | Antares 3A | Altair 3A | SGB Blk.1 | OIS |
| 4 Engine or Motor weight (lb) | 3,000 | 1,000 | 100 | | |
| 5 Propellant weight (lb) | 8,000 | 3,000 | 600 | | |
| 6 Stage number | 2 | 3 | 4 | upstage 2 | upstage 1 |
| 7 Oxidizer Fuel | solid | solid | solid | solid | solid |
| 8 Mixture ratio (O/F) | | | | | |
| 9 [illegible] | | | | | |
| 10 Length Diameter (ft)/(ft) | 20.7/2.59 | 11.2/2.49 | 12.4/3.50 | 5.2/4.6 | 5.9/4.6 |
| 11 Thrust (sea lev) (lb) * lb-sec | | | | | |
| 12 Thrust (vacuum) (lb) | 63,970 | 18,700 | 5,710 | 15,500 | 6,000 |
| 13 Chamber pressure (psia) | 700 | 700 | 670 | | |
| 14 Spec impuls (sea level) | | | | | |
| 15 Spec impuls (vacuum) (sec) | 280 | 295 | 288 | | |
| 16 Total burn time (sec) | 35.32 | 43.96 | 29.30 | | |
| 17 Nozzle expansion ratio | 21.2 | 46.0 | 50.3 | | |
| 18 Nozzle exit area (sq ft) | 7.95 | 4.48 | 1.5 | | |
| 19 Engine cant angle (deg) | 0 | 0 | 0 | | |
| 20 Case material | | | | | |
| 21 Case segment number | | | | | |
| 22 Thrust vector control (T.V.C) | H2O2 RCS | H2O2 RCS | Spin Stabilized | | |
| 23 Thrust coefficent Cf | 1.692 | 1.905 | 1.985 | | |
| 24 Nozzle discharge coefficent Cd g | 6.04E-3 | 6.46E-3 | 6.89E-3 | | |
| 25 Engine cycle | | | | | |
| 26 Mass Discharge Rate (lb/sec) | 228.5 | 63.4 | 19.8 | | |
| 27 Engine cost | | | | | |
| 28 Engine Reliability | | | | | |
| 29 Vehicle Name | Scout | Scout | Scout | Stage Vehicle System | Orbit Insertion Sys |

# DATA SUMMARY SHEET

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| NO. | ENGINE or MOTOR NAME | MOTOR 16 THIOKOL (MM3) | MOTOR 17 THIOKOL PAM-DII | MOTOR 18 UTC SRM-1 | MOTOR 19 UTC SRM-2 | MOTOR 20 Thiokol Castor 2 |
|---|---|---|---|---|---|---|
| 1 | User Agency | NASA | Varies | USAF | NASA | NASA, USAF |
| 2 | Manufacturer | Thiokol | Thiokol | UTC | UTC | Thiokol |
| 3 | Designation (stage or motor) | PAM-A | PAM DII | Boeing Orbital Sciences | Boeing | Castor 2A |
| 4 | Engine or Motor weight (lb) | | | | | |
| 5 | Propellant weight (lb) | | | | | |
| 6 | Stage number | upstage 1 | upstage 1 | 3 | 3 | 2 |
| 7 | Oxidizer/Fuel | solid | solid | solid | solid | solid |
| 8 | Mixture ratio (O/F) | | | | | |
| 9 | Coolant | | | | | |
| 10 | Length/Diameter (ft)/(ft) | 7.5/5.0 | 6.5/5.3 | 10.7/9.5 | 5.7/9.5 | |
| 11 | Thrust(sea lev) (lb) * = lb.sec | | | | | |
| 12 | Thrust (vacuum) (lb) | 35,200 | 17,600 | 44,100 | 16,800 | 61,800 |
| 13 | Chamber pressure (psia) | | | | | |
| 14 | Spec impuls (sea level) | | | | | |
| 15 | Spec. impuls (vacuum) (sce) | | | | | |
| 16 | Total burn time (sec) | | | | | |
| 17 | Nozzle expansion ratio | | | | | |
| 18 | Nozzle exit area (ftxft) | | | | | |
| 19 | Engine cant angle (deg) | | | | | |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | | | | | |
| 23 | Thrust Coeffiecnt Cf | | | | | |
| 24 | Nozzle discharge coefficent Cd g | | | | | |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | | | | | |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | | | | | |
| 29 | Vehicle Name | STS/PAM-A | STS/PAM-DII | Titan 4 IUS Transfer orbit stage | Titan 4 IUS | Scont SLV-1A |

| NUM | ENGINE or MOTOR NAME | MOTOR 21 Thiokol Antares 3 | MOTOR 22 Thiokol Altair 3 | MOTOR 23 Hercules X259-B4 | MOTOR 24 Thiokol Castor 4H | MOTOR 25 Thiokol Star-30 |
|---|---|---|---|---|---|---|
| 1 | User Agency | NASA, USAF | NASA, USAF | NASA, USAF | | |
| 2 | Manufacturer | Thiokol | Thiokol | Hercules | Thiokol | Thiokol |
| 3 | Designation (stage or motor) | Antares 3 | Altair 3 | Antares 2B | Castor 4H | Star-30 |
| 4 | Engine or Motor weight (lb) | | | | | |
| 5 | Propellant weight (lb) | | | | | |
| 6 | Stage number | 3 | 4 | 3 | 1,2 | 4 |
| 7 | Oxidizer/Fuel | solid | solid | solid | solid | solid |
| 8 | Mixture ratio (O/F) | | | | | |
| 9 | Coolant | | | | | |
| 10 | Length/Diameter (ft)/(ft) | | | | | |
| 11 | Thrust(sea lev) (lb) * = lb.sec | | | | | |
| 12 | Thrust (vacuum) (lb) | 21,000 | 5,700 | 28,000 | 138,000 | 7,500 |
| 13 | Chamber pressure (psia) | | | | | |
| 14 | Spec. impuls (sea level) | | | | | |
| 15 | Spec. impuls (vacuum) (sec) | | | | | |
| 16 | Total burn time (sec) | | | | | |
| 17 | Nozzle expansion ratio | | | | | |
| 18 | Nozzle exit area (ftxft) | | | | | |
| 19 | Engine cant angle (deg) | | | | | |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | | | | | |
| 23 | Thrust Coeffiecnt Cf | | | | | |
| 24 | Nozzle discharge coefficent Cd g | | | | | |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | | | | | |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | | | | | |
| 29 | Vehicle Name | Scout SLV-1A | Scout SLV-1A | Scout SLV-1A | Conestoge II | Conestoge II |

| NUM | ENGINE or MOTOR NAME | MOTOR 26 Thiokol TE-M-364-2 | MOTOR 27 Thiokol TE-M-442-1 | Motor 28 Thiokol TE-M-360 4 | | |
|---|---|---|---|---|---|---|
| 1 | User Agency | USAF | USAF | USAF | | |
| 2 | Manufacturer | Thiokol | Thiokol | Thiokol | | |
| 3 | Designation (stage or motor) | Burner 2, 2A | Burner 2A | S65 | | |
| 4 | Engine or Motor weight (lb) | | | | | |
| 5 | Propellant weight (lb) | | | | | |
| 6 | Stage number | upstage (varies) | upstage 2 | upstage 2 | | |
| 7 | Oxidizer/Fuel | solid | solid | solid | | |
| 8 | Mixture ratio (O/F) | | | | | |
| 9 | Coolant | | | | | |
| 10 | Length/Diameter (ft)/(ft) | 5.8/5.2 | 5.8/5.2 | 10.0/4.5 | | |
| 11 | Thrust(sea lev) (lb) * = lb.sec | | | | | |
| 12 | Thrust (vacuum) (lb) | 10,000 | 8,000 | 7,325 | | |
| 13 | Chamber pressure (psia) | | | | | |
| 14 | Spec impuls (sea level) | | | | | |
| 15 | Spec. impuls (vacuum) (sce) | | | | | |
| 16 | Total burn time (sec) | | | | | |
| 17 | Nozzle expansion ratio | | | | | |
| 18 | Nozzle exit area (ftxft) | | | | | |
| 19 | Engine cant angle (deg) | | | | | |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | | | | | |
| 23 | Thrust Coeffiecnt Cf | | | | | |
| 24 | Nozzle discharge coefficent Cd g | | | | | |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | | | | | |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | | | | | |
| 29 | Vehicle Name | Burner 2, 2A | Burner 2A | Stage Vehicle sys | | |

| NUM | ENGINE or MOTOR NAME | ENGINE 1 Aerojet LR-87-AJ-11 | ENGINE 2 Aerojet LR-91-AJ-11 | ENGINE 3 Aerojet AJ10-138 | ENGINE 4 Aerojet LR-87-AJ-5 | ENGINE 5 Aerojet LR-91-AJ-5 |
|---|---|---|---|---|---|---|
| 1 | User Agency | USAF, Commercial | USAF, Commercial | USAF | USAF | USAF |
| 2 | Manufacturer | Aerojet | Aerojet | Aerojet | Aerojet | Aerojet |
| 3 | Designation (stage or motor) | | | Transtage | | |
| 4 | Engine or Motor weight (lb) | | | | | |
| 5 | Propellant weight (lb) | 294,000 | 69,000 | 9,000 | | |
| 6 | Stage number | 1 | 2 | 3 | 1 | |
| 7 | Oxidizer/fuel | N2O4/N2H4-UDMH | N2O4/N2H4-UDMH | N2O4/N2H4-UDMH | N2O4/N2H4-UDMH | N2O4/N2H4-UDMH |
| 8 | Mixture ratio (O/F) | | | | | |
| 9 | Coolant | | | | | |
| 10 | Length/Diameter (ft)/(ft) | | | | | |
| 11 | Thrust*(sea lev) (lb) * = lb.sec | 264,500 / 273,000 | | | 215,000 | |
| 12 | Thrust (vacuum) (lb) | | 101,000 / 104,000 | 8,000 | | 100,000 |
| 13 | Chamber pressure (psia) | | | | | |
| 14 | Spec impuls (sea level) | | | | | |
| 15 | Spec. impuls (vacuum) (sec) | | | | | |
| 16 | Total burn time (sec) | | | | | |
| 17 | Nozzle expansion ratio | | | | | |
| 18 | Nozzle exit area (ftxft) | | | | | |
| 19 | Engine cant angle (deg) | | | | | |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | | | | | |
| 23 | Thrust Coeffiecnt Cf | | | | | |
| 24 | Nozzle discharge coefficent Cd g | | | | | |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | | | | | |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | | 0.9800 | | | |
| 29 | Vehicle Name | Titan 34D, 3, 4CGP, 41US | Titan 34D, 3, 4CGP, 41US | Titan 34D | Titan 2 SLV | Titan 2 SLV |

| NUM | ENGINE or MOTOR NAME | ENGINE 6 Rocket. YLR-89-NA7 | ENGINE 7 Rocket. YLR-105-NA7 | ENGINE 8 P&W RL10A-3-3A | ENGINE 9 Rocket. RS-27 | ENGINE 10 TRW TR201 |
|---|---|---|---|---|---|---|
| 1 | User Agency | NASA | NASA | NASA | NASA, USAF | NASA |
| 2 | Manufacturer | Rocketdyne | Rocketdyne | P&W | Rocketdyne | TRW |
| 3 | Designation (stage or motor) | MA-5 | | Centaur | ELT Thor | Delta |
| 4 | Engine or Motor weight (lb) | | | | | |
| 5 | Propellant weight (lb) | 111,506 | 77,825 | 14,867 | 175,000 | 10,000 |
| 6 | Stage number | 1/2 | 1 | 2 | 1 | 2 |
| 7 | Oxidizer/Fuel | LOX/RP-1 | LOX/RP-1 | LOX/LH2 | LOX/RP-1 | N2O2/N2H4-UDMH |
| 8 | Mixture ratio (O/F) | 2.25 | 2.22 | 5.0 | 2.23 | 1.6 |
| 9 | Coolant | | | | | |
| 10 | Length/Diameter (ft)/(ft) | | | | | |
| 11 | Thrust(sea lev) (lb) * = lb.sec | 188,750 | 60,500 | | 205,000 | |
| 12 | Thrust (vacuum) (lb) | | | 16,500 | 229,600 | 9,530 |
| 13 | Chamber pressure (psia) | 650 | 733 | 474 | 650 | 100 |
| 14 | Spec impuls (sea level) | 259 | 220 | | 261 | |
| 15 | Spec. impuls (vacuum) (sce) | 292 | 312 | 446.4 | 294 | 303 |
| 16 | Total burn time (sec) | 153 | 283 | 404 | 227 | 318 |
| 17 | Nozzle expansion ratio | 8 | 25 | 61 | 8 | 46 |
| 18 | Nozzle exit area (ftxft) | 11.24 | 11.56 | 8.22 | 12.0 | 17.4 |
| 19 | Engine cant angle (deg) | 0 | 0 | 0 | 0 | 0 |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | Gimballed Engines and Verniers | Gimballed Engines and Verniers | Gimballed Engines | Gimballed Engine | Gimballed Engine |
| 23 | Thrust Coeffiecnt Cf | 1.44 | 1.24 | 1.79 | 1.46 | 1.75 |
| 24 | Nozzle discharge coefficent Cd g | 5.54e-3 | 5.64e-3 | 4.01e-3 | 5.59e-3 | 5.78e-3 |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | 728.8 | 275.0 | 37.0 | 785.4 | 31.45 |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | 0.9907 | 0.9905 | 0.9854 | 0.9833 | 0.9774 |
| 29 | Vehicle Name | Atlas G Centaur D-1A/Atlas H | Atlas G, Centaur D-1A/Atlas H | Atlas G,Centaur D-1A /D-1T, Titan 4CGP | Delta3914/3924/6920/6925,3910/3920/PAM-D | Delta 3914/3924 3910/3920/PAM-D |

# DATA SUMMARY SHEET



| NUM | ENGINE or MOTOR NAME | ENGINE 11 Aerojet AJ10-118k | ENGINE 12 Rocket. RS-51 | ENGINE 13 P&W RL10A-3-3B | ENGINE 14 Rocket. LR-89_NA5 | ENGINE 15 Rocket. LR-105-NA5 |
|---|---|---|---|---|---|---|
| 1 | User Agency | NASA,USAF | Varies | USAF | USAF | USAF |
| 2 | Manufacturer | Aerojet | Rocketdyne | P&W | Rocketdyne | Rocketdyne |
| 3 | Designation (stage or motor) | Delta | AMS | Centaur | MA-3 | MA-3 |
| 4 | Engine or Motor weight (lb) | | 2,790 | | | |
| 5 | Propellant weight (lb) | 13,200 | | | | |
| 6 | Stage number | 2 | upstage | upstage | 1/2 | 1 |
| 7 | Oxidizer/Fuel | N2O2/N2H4-UDMH | N2O4/MMH | LOX/LH2 | LOX/RP-1 | LOX/RP-1 |
| 8 | Mixture ratio (O/F) | 1.9 | | | | |
| 9 | Coolant | | | | | |
| 10 | Length/Diameter (ft)/(ft) | | | | | |
| 11 | Thrust(sea lev) (lb) * = lb.sec | | | | 165,000 | 60,000 |
| 12 | Thrust (vacuum) (lb) | 9,710 | 2,650 | 15,000 | | |
| 13 | Chamber pressure (psia) | 114 | | | | |
| 14 | Spec impuls (sea level) | | | | | |
| 15 | Spec. impuls (vacuum) (sce) | 320.2 | | | | |
| 16 | Total burn time (sec) | 43532 | | | | |
| 17 | Nozzle expansion ratio | 65.2 | | | | |
| 18 | Nozzle exit area (ftxft) | 19.9 | | | | |
| 19 | Engine cant angle (deg) | 0 | | | | |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | Gimballed Engine | | | | |
| 23 | Thrust Coeffiecnt Cf | 1.93 | | | | |
| 24 | Nozzle discharge coefficent Cd g | 6.03e-3 | | | | |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | 30.32 | | | | |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | 0.9774 | | | | |
| 29 | Vehicle Name | Delta3914/3924/7920/7925,3910/3920/PAM-D | Stage | STS/Centaur 9 | Atlas E | Atlas E |

| NUM | ENGINE or MOTOR NAME | ENGINE 16 Bell 8096 | ENGINE 17 AGC Trnstge | | | |
|---|---|---|---|---|---|---|
| 1 | User Agency | USAF, NASA | NASA | | | |
| 2 | Manufacturer | Bell | AGC | | | |
| 3 | Designation (stage or motor) | YLR-81BA-11 | Delta | | | |
| 4 | Engine or Motor weight (lb) | | | | | |
| 5 | Propellant weight (lb) | | | | | |
| 6 | Stage number | upstage (varies) | 2 | | | |
| 7 | Oxidizer/Fuel | IRFNA/UDMH | N202/A-50 | | | |
| 8 | Mixture ratio (O/F) | | | | | |
| 9 | Coolant | | | | | |
| 10 | Length/Diameter (ft)/(ft) | | | | | |
| 11 | Thrust(sea lev) (lb) * = lb.sec | | | | | |
| 12 | Thrust (vacuum) (lb) | 16,000 | 10,000 | | | |
| 13 | Chamber pressure (psia) | | | | | |
| 14 | Spec impuls (sea level) | | | | | |
| 15 | Spec. impuls (vacuum) (sce) | | | | | |
| 16 | Total burn time (sec) | | | | | |
| 17 | Nozzle expansion ratio | | | | | |
| 18 | Nozzle exit area (ftxft) | | | | | |
| 19 | Engine cant angle (deg) | | | | | |
| 20 | Case material | | | | | |
| 21 | Case segment number | | | | | |
| 22 | Thrust vector control (T.V.C) | | | | | |
| 23 | Thrust Coeffiecnt Cf | | | | | |
| 24 | Nozzle discharge coefficent Cd g | | | | | |
| 25 | Engine cycle | | | | | |
| 26 | Mass Discharge Rate (lb/sec) | | | | | |
| 27 | Engine cost | | | | | |
| 28 | Engine Reliability | | | | | |
| 29 | Vehicle Name | Agena D | Delta 3920/PAM-D | | | |

# TABLE 1: RELIABILITY COMPARISON OF U.S. LAUNCH VEHICLE FAMILIES

| | Vehicle Name Data Collection Period | Thor / Delta | | | Titan | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thor 57-63 | Delta 60-87 | Combine 57-87 | Titan I 59-65 | Titan II 62-76 | Titan III 64-87 | Titan 34D 82-87 | Combine 59-87 |
| | Success Ratio: Mean | 0.8982 | 0.9402 | 0.9192 | 0.6427 | 0.8864 | 0.9405 | 0.7355 | 0.8013 |
| | 5% | 0.8750 | 0.9110 | 0.8789 | 0.5665 | 0.8323 | 0.9055 | 0.4976 | 0.8075 |
| | 95% | 0.9181 | 0.9615 | 0.9551 | 0.7202 | 0.9272 | 0.9651 | 0.8990 | 0.9546 |
| STAGE NO. | Stage 0 | 0.9965 | 0.9950 | | | | 0.9946 | 0.8678 | |
| | Stage 1/2 | | | | | | | | |
| | Stage 1 | 0.9346 | 0.9850 | | 0.8214 | 0.8574 | | 0.8476 | |
| | Stage 2 | 0.9764 | 0.9746 | | 0.7825 | 0.9258 | 0.9763 | | |
| | Stage 3 | 0.9877 | 0.9843 | | | | 0.9667 | | |
| | Stage 4 | | | | | | | | |
| SYSTEM | Propulsion | 0.9544 | 0.8701 | | 0.6725 | 0.9280 | 0.9622 | 0.7355 | |
| | Guidance | 0.9830 | 0.9850 | | | 0.9929 | 0.9892 | | |
| | Flight Control | 0.9907 | 0.9851 | | | 0.9858 | 0.9946 | | |
| | Structure | 0.9980 | | | 0.9702 | | 0.9946 | | |
| | Electrical | 0.9815 | 0.9850 | | | 0.9929 | | | |
| | Separation | 0.9969 | 0.9950 | | | 0.9856 | | | |
| | Other or (UK) | 0.9923 | | | | | | | |

| | Vehicle Name Data Collection Period | Atlas | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Atlas A 57-58 | Atlas B 58-59 | Atlas C 58-59 | Atlas D 59-67 | Atlas E 60-66 | Atlas F 61-81 | Atlas SLV 67-83 | Atlas G 84-87 | Atlas H 83-87 | Atlas/Centaur 62-87 | Combine 57-88 |
| | Success Ratio: Mean | 0.4218 | 0.5556 | 0.5833 | 0.8401 | 0.7426 | 0.8863 | 0.9445 | no failure | no failure | 0.9089 | 0.7883 |
| | 5% | 0.1827 | 0.3010 | 0.2642 | 0.8015 | 0.6454 | 0.8359 | 0.8736 | 0.6313 | 0.6313 | 0.8450 | 0.4781 |
| | 95% | 0.6977 | 0.7896 | 0.8565 | 0.8734 | 0.8240 | 0.9276 | 0.9652 | | | 0.9489 | 0.9953 |
| STAGE NO. | Stage 0 | | | | | | | | | | | |
| | Stage 1/2 | | | | | 0.8713 | 0.9573 | 0.986 | | | 0.9814 | |
| | Stage 1 | | | | | 0.8523 | 0.9279 | 0.9716 | | | 0.9810 | |
| | Stage 2 | | | | | | | 0.9856 | | | 0.9420 | |
| | Stage 3 | | | | | | | | | | | |
| | Stage 4 | | | | | | | | | | | |
| SYSTEM | Propulsion | 0.8844 | 0.6667 | | | 0.8713 | 0.9212 | 0.9824 | | | 0.9535 | |
| | Guidance | | | | | 0.9571 | 0.9889 | | | | | |
| | Flight Control | 0.7886 | 0.8889 | | | 0.9428 | 0.9889 | 0.9824 | | | 0.9907 | |
| | Structure | 0.7666 | | | | 0.9857 | | | | | 0.9814 | |
| | Electrical | | | | | 0.9857 | | 0.9824 | | | 0.9907 | |
| | Separation | | | | | | | 0.9824 | | | 0.9907 | |
| | Other or (UK) | | | | | | 0.9934 | | | | | |

| | Vehicle Name Data Collection Period | Saturn "Family" | | | | | | Scout "Family" | | | STS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Jupiter 58-58 | Juno 58-61 | Saturn I 62-65 | Saturn IB 66-75 | Saturn V 67-73 | Combine 58-75 | Vanguard 57-59 | Scout 60-88 | Combine 57-88 | Space Shuttle 81-88 |
| | Success Ratio: Mean | 0.3811 | 0.4300 | no failure | no failure | 0.9822 | 0.7547 | 0.3388 | 0.9420 | 0.8404 | 0.9275 |
| | 5% | 0.1026 | 0.2135 | 0.7943 | 0.7743 | 0.8180 | 0.2852 | 0.1556 | 0.9023 | 0.1821 | 0.8147 |
| | 95% | 0.6879 | 0.8743 | | | 0.9987 | 0.9935 | 0.5723 | 0.9683 | 0.8744 | 0.9806 |
| STAGE NO. | Stage 0 | | | | | | | | | | |
| | Stage 1/2 | | | | | | | | | | |
| | Stage 1 | | 0.8575 | | | | | 0.8347 | 0.9817 | | 0.9275 |
| | Stage 2 | 0.5741 | 0.7009 | | | 0.9822 | | 0.5046 | 0.9875 | | |
| | Stage 3 | | 0.7828 | | | 0.9822 | | 0.8289 | 0.9746 | | |
| | Stage 4 | 0.8290 | 0.9378 | | | | | | 0.9870 | | |
| SYSTEM | Propulsion | 0.7870 | | | | | | 0.7521 | 0.9793 | | 0.9275 |
| | Guidance | | | | | | | 0.9174 | 0.9817 | | |
| | Flight Control | | | | | | | 0.8347 | 0.9817 | | |
| | Structure | | | | | | | | | | |
| | Electrical | | | | | | | | 0.9878 | | |
| | Separation | 0.5741 | | | | | | | 0.9959 | | |
| | Other or (UK) | | | | | | | 0.8347 | 0.9959 | | |

## TABLE 1A: RELIABILITY OF THE THOR/DELTA FAMILY

| Vehicle Name<br>Data Collection<br>Period | | Thor / Delta | | |
|---|---|---|---|---|
| | | Thor<br>57-83 | Delta<br>60-87 | Combine<br>57-87 |
| Success Ratio: Mean<br>5%<br>95% | | 0.8982<br>0.8750<br>0.9181 | 0.9402<br>0.9110<br>0.9615 | 0.9192<br>0.8789<br>0.9551 |
| STAGE NO. | Stage 0 | 0.9965 | 0.9950 | |
| | Stage 1/2 | | | |
| | Stage 1 | 0.9346 | 0.9850 | |
| | Stage 2 | 0.9764 | 0.9746 | |
| | Stage 3 | 0.9877 | 0.9843 | |
| | Stage 4 | | | |
| SYSTEM | Propulsion | 0.9568 | 0.9701 | |
| | Guidance | 0.9830 | 0.9950 | |
| | Flight Control | 0.9907 | 0.9851 | |
| | Structure | 0.9969 | | |
| | Electrical | 0.9815 | 0.9950 | |
| | Separation | 0.9969 | 0.9950 | |
| | Other or (UK) | 0.9923 | | |

## TABLE 1B: RELIABILITY OF THE TITAN FAMILY

| | Vehicle Name Data Collection Period | Titan | | | | |
|---|---|---|---|---|---|---|
| | | Titan I 59-65 | Titan II 62-76 | Titan III 64-87 | Titan 34D 82-87 | Combine 59-87 |
| | Success Ratio: Mean | 0.6427 | 0.8864 | 0.9406 | 0.7355 | 0.8013 |
| | 5% | 0.5585 | 0.8323 | 0.9055 | 0.4978 | 0.6075 |
| | 95% | 0.7202 | 0.9272 | 0.9651 | 0.8990 | 0.9546 |
| STAGE NO. | Stage 0 | | | 0.9946 | 0.8678 | |
| | Stage 1/2 | | | | | |
| | Stage 1 | 0.8214 | 0.9574 | | 0.8476 | |
| | Stage 2 | 0.7825 | 0.9258 | 0.9783 | | |
| | Stage 3 | | | 0.9667 | | |
| | Stage 4 | | | | | |
| SYSTEM | Propulsion | 0.6725 | 0.9290 | 0.9622 | 0.7355 | |
| | Guidance | | 0.9929 | 0.9892 | | |
| | Flight Control | | 0.9858 | 0.9946 | | |
| | Structure | 0.9702 | | 0.9946 | | |
| | Electrical | | 0.9929 | | | |
| | Separation | | 0.9858 | | | |
| | Other or (UK) | | | | | |

# TABLE 1C: RELIABILITY OF THE ATLAS FAMILY

| Vehicle Name Data Collection Period | | Atlas | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Atlas A 57-58 | Atlas B 58-59 | Atlas C 58-59 | Atlas D 59-67 | Atlas E 60-88 | Atlas F 61-81 | Atlas SLV 67-83 | Atlas G 84-87 | Atlas H 83-67 | Atlas/ Centaur 62-87 | Combine 57-88 |
| Success Ratio: Mean | | 0.4219 | 0.5558 | 0.5833 | 0.8401 | 0.7426 | 0.8883 | 0.9445 | no failure | no failure | 0.9069 | 0.7883 |
| 5% | | 0.1827 | 0.3010 | 0.2642 | 0.8015 | 0.6454 | 0.8359 | 0.8736 | 0.6313 | 0.6313 | 0.8450 | 0.4761 |
| 95% | | 0.6977 | 0.7896 | 0.8585 | 0.8734 | 0.8240 | 0.9276 | 0.9652 | | | 0.9489 | 0.9953 |
| STAGE NO. | Stage 0 | | | | | | | | | | | |
| | Stage 1/2 | | | | | 0.8713 | 0.9573 | 0.9861 | | | 0.9814 | |
| | Stage 1 | | | | | 0.8523 | 0.9279 | 0.9719 | | | 0.9810 | |
| | Stage 2 | | | | | | | 0.9856 | | | 0.9420 | |
| | Stage 3 | | | | | | | | | | | |
| | Stage 4 | | | | | | | | | | | |
| SYSTEM | Propulsion | 0.8844 | 0.6667 | | | 0.8713 | 0.9212 | 0.9824 | | | 0.9535 | |
| | Guidance | | | | | 0.9571 | 0.9869 | | | | | |
| | Flight Control | 0.7688 | 0.8889 | | | 0.9428 | 0.9869 | 0.9824 | | | 0.9907 | |
| | Structure | 0.7688 | | | | 0.9857 | | | | | 0.9814 | |
| | Electrical | | | | | 0.9857 | | 0.9824 | | | 0.9907 | |
| | Separation | | | | | | | 0.9824 | | | 0.9907 | |
| | Other or (UK) | | | | | | 0.9934 | | | | | |

# TABLE 1D: RELIABILITY OF THE SATURN FAMILY

| Vehicle Name Data Collection Period | | Saturn "Family" | | | | | |
|---|---|---|---|---|---|---|---|
| | | Jupiter 58-58 | Juno 58-61 | Saturn I 62-65 | Saturn IB 66-75 | Saturn V 67-73 | Combine 58-75 |
| Success Ratio: Mean<br>5%<br>95% | | 0.3611<br>0.1026<br>0.6879 | 0.4300<br>0.2135<br>0.6743 | no failure<br>0.7943 | no failure<br>0.7743 | 0.9822<br>0.8180<br>0.9997 | 0.7547<br>0.2652<br>0.9935 |
| STAGE NO. | Stage 0 | | | | | | |
| | Stage 1/2 | | | | | | |
| | Stage 1 | | 0.8575 | | | | |
| | Stage 2 | 0.5741 | 0.7009 | | | 0.9822 | |
| | Stage 3 | | 0.7629 | | | 0.9822 | |
| | Stage 4 | 0.6290 | 0.9378 | | | | |
| SYSTEM | Propulsion | 0.7870 | | | | | |
| | Guidance | | | | | | |
| | Flight Control | | | | | | |
| | Structure | | | | | | |
| | Electrical | | | | | | |
| | Separation | 0.5741 | | | | | |
| | Other or (UK) | | | | | | |

## TABLE 1E: RELIABILITY OF THE SCOUT FAMILY

| Vehicle Name<br>Data Collection<br>Period | | Scout "Family" | | |
|---|---|---|---|---|
| | | Vanguard<br>57-59 | Scout<br>60-88 | Combine<br>57-88 |
| Success Ratio: Mean<br>5%<br>95% | | 0.3388<br>0.1555<br>0.5723 | 0.9420<br>0.9023<br>0.9683 | 0.6404<br>0.1821<br>0.9744 |
| STAGE NO. | Stage 0 | | | |
| | Stage 1/2 | | | |
| | Stage 1 | 0.8347 | 0.9917 | |
| | Stage 2 | 0.5049 | 0.9875 | |
| | Stage 3 | 0.8039 | 0.9746 | |
| | Stage 4 | | 0.9870 | |
| SYSTEM | Propulsion | 0.7521 | 0.9793 | |
| | Guidance | 0.9174 | 0.9917 | |
| | Flight Control | 0.8347 | 0.9917 | |
| | Structure | | | |
| | Electrical | | 0.9876 | |
| | Separation | | 0.9959 | |
| | Other or (UK) | 0.8347 | 0.9959 | |

## TABLE 1F: RELIABILITY OF THE SPACE SHUTTLE

| | | |
|---|---|---|
| Vehicle Name<br>Data Collection<br>Period | | STS<br>Space Shuttle<br>81-88 |
| Success<br>Ratio: Mean<br>5%<br>95% | | 0.9275<br>0.8147<br>0.9806 |
| STAGE NO. | Stage 0 | |
| | Stage 1/2 | |
| | Stage 1 | 0.9275 |
| | Stage 2 | |
| | Stage 3 | |
| | Stage 4 | |
| SYSTEM | Propulsion | 0.9275 |
| | Guidance | |
| | Flight Control | |
| | Structure | |
| | Electrical | |
| | Separation | |
| | Other or (UK) | |

system of reliability techniques can lead designers and decision makers to make incorrect decisions even if correctly applied as is demonstrated below. Finally, it appears that the currently institutionalized reliability technology base, because of its qualitative nature, will be unable to address just the residual reliability related issues such as residual variability reduction, risk management and human reliability that limit launch systems to their current operational reliability levels.

Here are some examples why. The examples fall into two broad categories: either they are the result of performing FMEAs/FMECAs or quantitative reliability analysis.

### 1.3.1 FMEAs/FMECAs

FMEAs/FMECAs are structured to detect single point failures. When single point failures are identified they are either controlled or compensated for by use of redundancy.

Redundancy and Correlation Factors - When applied to electronics, redundancy can be a very effective way to enhance reliability. However, as Section 2.3.1.2, "Product Design FMEAs" points out, even electronics can be susceptible to "common cause" or "correlation" failure. These are the types of failures that can negate the benefits of redundancy due to a single event. Product Design FMEAs have proven beneficial in reducing vulnerability to correlated failures in electronics systems and may prove to be beneficial in the analysis of propulsion systems. None-the-less, propulsion systems, like any high energy system, are inherently more vulnerable to correlated failures. This is supported by the study of the shuttle main engine development history which is summarized in Section 2.1.4 and provided in detail in Appendix A.1 "An Investigation of Historical Failure Correlation Factors Using the Shuttle SSME Flight History as an Example."

Controls and Variability - When redundancy, for whatever reason, is not an option when conducting an FMEA, the failure mode is "controlled" either by designing the failure mechanism directly out of the system or by placing more stringent controls on manufacturing and/or testing. Designing a failure mechanism out is usually not a viable option because it requires a physically different way of obtaining the same function. Thus, manufacturing or testing is the most practical way of constraining the failure mode. The only problem with this approach is that if methods are not in place to measure the effects in terms of reduced variability, there is no way to measure the impact on reliability.

Reusability - Another potential problem with FMEAs is that they tend not to be "living" documents in the sense that if a system is reused or is reusable, the FMEA is not structured to handle the potential results. For instance, weld failures on the Space Shuttle Main Engine can result from thermal cycling and fatigue through reuse. The FMEA is not structured to conveniently handle this situation.

"Bottom Up" Methodology - As has been previously discussed, FMEAs/FMECAs are "bottom up" methodologies and as such are not designed to list all potential malfunctions of a system, only those which propagate from known failure modes of components within the system. Without a comprehensive way of anticipating system or subsystem malfunctions in a global sense, the analyst can never be comfortable that the FMEA/FMECA is exhaustive. A "Top Down" methodology as described in Section 2.3.1.2 would help overcome this "Bottom Up" obstacle.

1.3.2 Quantitative Reliability Analysis

In order for quantitative reliability analysis to be effective the three following constituents must be present:

1. Meaningful Reliability Data/Issues
2. Proper Reliability Analysis Tools
3. Risk Analysis and Management Capabilities

Meaningful Reliability Data/Issues - For the current generation of launch vehicles, the historical data set (see Appendices A.1 and A.3) appears to be both meaningful and capable of addressing the key reliability issues. To be meaningful, the reliability data must:

1. Be complete for both success and failure.

2. Have failure causes consistently identified.

3. Have chronologies of failure history established.

4. Have design change chronologies established.

In order to be effective, however, the following issues must be resolved:

1. How relevant is history in predicting future performance in a developmental system?

2. How is historical reliability growth to be accounted for?
- old failures less than new?
- How are design changes factored in?

3. What effect does hold down time just prior to launch have on prevention of failures which otherwise would occur after launch?

These issues can only be addressed by applying the appropriate quantitative reliability models using a properly developed and structured historical data set.

Quantitative Reliability Analysis Tools Specifically for Propulsion Systems - Until now the only quantitative methodology available for propulsion systems which addresses the developmental nature of such systems have been traditional reliability growth methods (such as the Duane approach and Weibull methods) and D. Lloyd's methodology (see Section 2.2.2). Even if these methodologies were adequate in addressing overall launch vehicle reliability, three other areas should be considered in order for a quantitative reliability analysis to be fully effective.

They are:

- Estimation of Stage Reliability

- Estimation of System Reliability

- Estimation of Engine or Motor Reliability

A method of estimating launch vehicle reliability is summarized in Section 2.2.1 and all four methods are described in detail in Appendix A.3, "Reliability Analysis for Current US Launch Vehicles".

Risk Assessment/Management - Section 1.3.1 has described the limited value of FMEAs/FMECAs in the quantification of reliability. Although they are useful in constructing logic models (see reliability techniques, Figure 2), strictly speaking they can only be used to quantify consequences. For instance, they can be used to quantify total number of welds whose failure could cause loss of an engine, cluster, stage, or vehicle (consequences), but this approach does not provide the analyst with the quantitative risk discriminating information required of a decision making tool. A decision making tool allows the analyst to rank individual weld failures, for example, with other sources of propulsion system failures in order to determine where to best expend resources. If a decision is made to expend the funds, the funds must be dedicated or "fenced off" and made distinct from management reserve funding. Even well developed criticality ranking techniques do not do the job sufficiently because they do not develop rankings at the system level but only at subsystem or lower levels, since their system level rankings are often developed only on a near relative basis. This approach can give the impression that a thrust vector control system single failure is just as important as other propulsion system elements such as a heat exchanger or turbopump, even though the latter may have several orders of magnitude higher failure probability. The solution to this problem is to use the quantitative reliability analysis tools of Section 1.3.2.2 in conjunction with Risk Analysis/Assessment techniques as described in Sections 2.3.1.3 and 2.3.2.

Figure 8 (Section 2.3) shows the relationship of risk management and assessment to infrastructure controls that have an impact on reliability.

# 2.0 (TASK 2) RELIABILITY ENHANCING METHODOLOGIES

## 2.1 Lessons Learned

This section is concerned with lessons learned either as a direct result of plant visits or from a related analysis.

### 2.1.1 Variability Control

Variability control was highlighted as a reliability enhancer at Hercules (West Virginia) and McDonnell Douglas (Huntington Beach, CA), as noted in Appendix B.

The Hercules trip indicated that solid rocket motors can achieve high reliabilities (>.999) and maintain these reliabilities over reasonable production runs (as many as 1000 units/year), if the proper reliability considerations are included in the design and development phases of the program and the proper process controls are in place, and if the proper test program remains in place. The process control system must be able not only to detect penetrations of the Upper Quality Limit (UQL) and Lower Quality Limit (LQL), but also trends toward unacceptable quality. These trends must be thoroughly investigated and tied to causes, the causes addressed, solutions derived and implemented, and control mechanisms directed at controlling key process parameters verified as being reestablished.

### 2.1.2 Reusability

Reusability is, on the surface, a design goal of significant program benefit. However, the benefits of reusability are significantly compromised if the reliability of an engine is adversely affected by the requirement for reuse. Besides the direct costs involved in developing a reusable design, there now appears to be a significant indirect cost required to maintain reliability in reusable design. For example, reusability by its very nature tends to decrease the production run. When production runs are decreased, investments in automated production equipment becomes less economical and the production process therefore tends to become more prototypical. Prototypical production, especially of complex equipment, increases the problem of variability control and therefore substantial post production testing may be required to ensure high reliabilities. A good example of such an indirect impact on reusability was seen at the Rocketdyne SSME production facility in Canoga Park, California.

### 2.1.3 Performance Indicators

For high reliability programs it is important to identify early on symptoms of the process which presage deterioration in performance. This has been done in the financial community by the development of a set of "leading" performance indicators and developing performance trends based upon the indicator trajectories through time. If such a set of indicators could be developed and trended for advanced propulsion system development programs, the indicator trajectories might provide early warning of problems arising during development and operation. This early warning could provide the time required to institute corrective action before actual program reliability performance is affected.

### 2.1.4 Correlation Factors (See Appendix A.1)

Given the current state of rocket engine technology, there exists a finite probability of catastrophic engine failure during a vehicle launch. A catastrophic engine failure is considered one in which the engine does not shut down in a controlled manner and includes uncontrolled fire, explosion, breach of the pressure boundary, shrapnel, complete loss of fuel or oxidizer supply, or a combination of these. Given that an engine

has failed catastrophically in flight, an immediate concern is for other critical hardware in the vicinity of the failed engine. For vehicles configured with multiple engines in a cluster, the question becomes whether the catastrophic failure of one engine will result in the catastrophic loss of the entire engine cluster.

In the present study, the correlation between a catastrophic failure of a Space Shuttle Main Engine (SSME) and the propagation of that failure to include the entire SSME three engine cluster has been developed based upon the SSME Test History.

Conclusions - In the development of future launch vehicles, the potential benefit of engine out capabilities must be weighed against the risks that if an engine fails in an uncontrolled manner, it will result in the loss of the entire engine cluster. This study evaluated the SSME which is flown in a three engine cluster. No uncontrolled SSME failures have occurred in flight. Only a limited amount of ground testing has actually been done in a three engine cluster and although failures have occurred, none have propagated to involve the entire cluster.

However, the test data evaluated here indicates there is a reasonable probability, approximately 17%, that an uncontrolled SSME failure will propagate to the adjacent engines given that an uncontrolled failure occurs. The confidence interval is between 4% and 41% that a failure will propagate to the cluster (at 95% confidence).

A summary of the results of the data review is given in Table 2.

2.1.5 Correlation vs. Engine Out Capability(See Appendix A.2)

A preliminary correlation factor vs engine out capability study was conducted using the following assumptions:

- Smaller engines are more reliable than larger ones.
- Increased plumbing due to a larger number of engines decreases reliability.

The results of the study indicate that a four engine configuration would be the most reliable if correlation factors are not taken into account.

When correlation factors are between 20 and 27% the four engine configuration is no better than a single engine configuration. Section 2.1.4 indicates that the 95% interval for correlation failure is 4 to 41%. Therefore, there is a substantial probability that correlated failure on an engine design which is comparable to the SSME could negate engine out capability.

TABLE 2: SSME CORRELATION OF FAILURE FACTOR

| 3.2 TEST NUMBER | DATE | ENG. | CONFIG | UCR | UNCNTD SHTDN | UNCONT HDWR FAILR | ENGN RETRO | APPLICBL FAILURE | SURRDG HARDWR DAMAGE * | CLUSTR DAMAGE ** | STAND DOWN TIME | R/L | COMP | COMMENT | TEST DURATN | C/O PWR LVL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 901.110 | 24-Mar-[illegible] | 0005 | [illegible] FMOF | [illegible] | YES | YES | YES | YES | NO | NO | 5 | [illegible] | HPOTP | HPOTP FIRE EXT DAM | 74.[illegible] | [illegible] |
| 901.[illegible] | [illegible]-Aug-[illegible] | 0004 | [illegible] FMOF | [illegible] | [illegible] | YES | NO | NO | | | 6 | [illegible] | FPB | HOLE IN FPB BODY | 48.2 | 90 |
| 90[illegible] | [illegible]-Sep-[illegible] | [illegible] | [illegible] FMOF | [illegible] | [illegible] | YES | YES | YES | NO | NO | [illegible] | [illegible] | HPOTP | HPOTP BRG FAILURE - EXT DAM | [illegible] | [illegible] |
| 902.[illegible] | [illegible]-Nov-[illegible] | [illegible] | [illegible] FMOF | [illegible] | [illegible] | [illegible] | NO | NO | | | [illegible] | [illegible] | HPOTP | [illegible] TURBINE BLADE [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | YES | YES | NO | NO | [illegible] | [illegible] | HPFTP | [illegible] TURB BL FAILURE | [illegible] | [illegible] |
| [illegible] | [illegible]-Mar-[illegible] | [illegible] | [illegible] FMOF | [illegible] | [illegible] | [illegible] | [illegible] | YES | NO | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] BURN [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] DAM | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | NO | [illegible] | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] FMOF | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] FMOF | [illegible] | [illegible] | [illegible] | NO | NO | | | [illegible] | [illegible] | [illegible] | MFV BODY FAILURE | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | YES | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] IN INJ/ OX POST [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | YES | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] DISPLACED [illegible] DAM | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | FMOF | [illegible] | [illegible] | [illegible] | NO | [illegible] | | | [illegible] | [illegible] | FPB | HOLE BURNED IN FPB | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | FMOF | [illegible] | [illegible] | YES | [illegible] | YES | NO | NO | [illegible] | [illegible] | FPB | FPB INJECTOR BURNT [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | FMOF | [illegible] | [illegible] | [illegible] | NO | NO | | | | | [illegible] | MAIN INJECTOR BURN [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | PHASE I | [illegible] | [illegible] | [illegible] | [illegible] | YES | NO | NO | [illegible] | [illegible] | MCC | [illegible] BURN CUT EXT DAM | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | PHASE I | [illegible] | [illegible] | [illegible] | NO | NO | | | [illegible] | [illegible] | [illegible] | [illegible] BURN OUT/REP[illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | PHASE I | [illegible] | YES | [illegible] | [illegible] | [illegible] | YES | NO | [illegible] | [illegible] | [illegible] | TURB BL FAIL/VOLUTE [illegible] EXT DAM | [illegible] | [illegible] |
| [illegible] | [illegible]-Oct-[illegible] | [illegible]107 | PHASE I | A018[illegible] | [illegible] | YES | NO | NO | | | [illegible] | [illegible] | HPFTP | HPFTP T/A DUCT S/M BULGED | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | PHASE I | A0[illegible] | YES | YES | YES | YES | NO | NO | [illegible] | [illegible] | [illegible] | [illegible] FROM EDM EXT DAMAGE (CG-1[illegible]) | [illegible] | [illegible] |
| [illegible] | [illegible]-Aug-[illegible] | [illegible] | PHASE I | [illegible] | YES | YES | YES | YES | YES | YES | [illegible] | [illegible] | HPFTP | RISER HAT/TURB BRG EXT DAM | [illegible] | [illegible] |
| [illegible] | [illegible]-Apr-[illegible] | [illegible]07 | PHASE I | | NO | NO | NO | NO | | | 3 | | OPOV | OPOV SEAL EROSION | [illegible] | |
| [illegible] | [illegible]-May-[illegible] | [illegible]19 | PHASE I | | NO | NO | YES | NO | | | 4[illegible] | | OPOV | OPOV SEAL CRACKED AND ERODED | 300.00 | |
| [illegible] | [illegible]-Aug-[illegible] | 2208 | PHASE I | A011[illegible] | YES | YES | YES | YES | YES | [illegible] | 63 | [illegible] | [illegible] | HPO DUCT RUPTURE - EXT DAM | [illegible] | [illegible] |
| [illegible] | [illegible]-Feb-84 | 2015 | PHASE I | | NO | NO | NO | NO | - | | | | OPB | OPB ASI CHAMBER EROSION | 527.8[illegible] | 65 |
| 901.43[illegible] | [illegible]-Feb-84 | [illegible] | PHASE II | A013[illegible] | YES | YES | YES | YES | NO | | 3[illegible] | [illegible] | [illegible] | [illegible] LNR PR MAJOR DAMAGE | 611.06 | 109 |
| 901.48[illegible] | [illegible]-Feb-85 | 0207 | PHASE II | A014585 | YES | NO | NO | NO | - | | 9 | [illegible] | FPB | CRACK AT F-13 FLANGE eng retired | 203.86 | 109 |
| 750.25[illegible] | [illegible]-Mar-85 | 2208 | PHASE II | A015713 | YES | YES | YES | YES | YES | [illegible] | 160 | [illegible] | [illegible] | DISCH MAN RUPTURE - EXT DAM | 101.47 | 109 |
| 750.2[illegible] | [illegible]-May-87 | [illegible] | PHASE II | | YES | YES | NO | NO | - | - | 26 | | NOZZLE | CLASS I NOZZLE LEAK | 223.56 | 109 |
| 902.427 | 26-Jun-87 | 2106 | PHASE II | | YES | NO | NO | NO | - | - | 5 | | DUCT | LPFTP TURBINE DISCHARGE DUCT FAIL/FIRE | 138.36 | 104 |
| 902.429 | 1-Jul-87 | 2106 | PHASE II | | YES | YES | NO | NO | - | - | 41 | | OPB | OPB INTERPROPELLANT PLATE CRACK | 204.12 | 104 |

NOTES:

ENG - ENGINE NUMBER
CONFIG - ENGINE CONFIGURATION
UCR - UNACCEPTABLE CONDITION REPORT
UNCNTD SHTDN - UNCONTROLLED ENGINE SHUTDOWN
UNCONT HDWR FAILR - UNCONTAINED HARDWARE FAILURE
ENGN RETRO - ENGINE RETIRED FOLLOWING THIS EVENT
APPLICBL FAILURE - FAILURE IS APPLICABLE TO THIS STUDY
SURRDG HARDWR DAMAGE - EVENT RESULTED IN DAMAGE TO SURROUNDING HARDWARE
CLUSTR DAMAGE - FAILURE WOULD RESULT IN DAMAGE TO THE ENGINE CLUSTER
STAND DOWN TIME - DAYS FROM THIS EVENT UNTIL THE NEXT TEST ON THIS STAND
R/L - REDLINE ISSUED FOR CUTOFF
COMP - MAJOR COMPONENT INVOLVED IN EVENT
C/O PWR LVL - CUTOFF POWER LEVEL

## 2.2 Historical Data Analysis

"Historical Data Analysis" is intended only to acquaint the reader with the various analytical options presently available. In fact, as is discussed in Section 3.0 (Comparison of the Methods of Section 2.2), there is insufficient information, as well as limited time and resources available to the study, to make a thorough comparison of methodologies. Further studies are, however, recommended as stated in the Recommendations Section.

### 2.2.1 Y. Shen's Methodology (Reliability Analysis for Launch Vehicles)

The performance history of any launch vehicle can be considered as having two time periods, the early development period and the stable performance period. During the early development period, the unreliability of a launch vehicle is generally high and unstable. After a "failure analysis and fix" process in combination with technical and design improvements, the unreliability of a launch vehicle goes down and stabilizes.

This effect of early transient behavior followed by stable reliability behavior is indicated in Table 11a for the Thor/Delta family and Table 11b for the Titan family. In both cases, oscillating reliability histories are observed early on with later stable performance. It is also interesting to note that Titan I appears to have never reached stability and the Delta, being based on the significant Thor history, reached a stable, high level of reliability very quickly.

These historical reliability growth curves are developed according to the following method.

The maximum-likelihood estimator (failure ratio) for unreliability can be defined as:

$$\hat{U} = F/L$$

Where F is a cumulative failure number, L is a cumulative launch number and F is a function of L.

The easiest way then to estimate the average unreliability of a launch vehicle is:

$$U_e = F/L \qquad (1)$$

*where $U_e$ is the estimated average unreliability, and F and L are the cumulative failure and launch numbers.*

As was mentioned before, the reliability growth effect must be considered to get a more realistic estimation of the unreliability. In the present model, the average unreliability is defined as

$$U = U_e - \Delta U \qquad (2)$$

where $\Delta U$ is the correction reliability caused by the reliability growth effect and can be explained as

$$\Delta U = \Delta F/L$$

or

$$\Delta F = \Delta U \cdot L \qquad (3)$$

where $\Delta F$ is the correction cumulative failure number.

Averaging both sides of equation (3), we get

$$\overline{\Delta F} = \Delta U \cdot \frac{L}{2}$$

or

$$\Delta U = \frac{2}{L} \cdot \overline{\Delta F} \qquad (4)$$

Substitute equation (1) and equation (4) into equation (2)

$$U = \frac{F}{L} - \frac{2}{L} \cdot \overline{\Delta F} \qquad (5)$$

The estimation of the unreliability of the launch vehicle at the nth launch can then be approximated as

$$U_n = \frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N} \left( F_i - \frac{F_n}{L_n} \cdot L_i \right)}{N} \qquad (6)$$

where $L_i$ is the $i^{th}$ launch number, and $F_i$ is the cumulative failure number at $i^{th}$ launch.

The reliability $R_n$ at the $n^{th}$ launch is

$$R_n = 1 - U_n = 1 - \left[ \frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N} \left( F_i - \frac{F_n}{L_n} \cdot L_i \right)}{N} \right] \qquad (7)$$

The concepts of confidence level based on the value of average reliability from equation (7) are now illustrated as the following.

Let N be the launch number, then $X = N \cdot R_n$ is the success number. In this case, the 5th percentile confidence is given by -

$$R_{0.05} = \frac{x}{x + (n - x + 1) F_{0.95}(2n - 2x + 2,\ 2x)} \qquad (8)$$

and the 95th percentile confidence is given by-

$$R_{0.95} = \frac{(x+1) F_{0.95}(2x+2, 2n-2x)}{(n-x) + (x+1) F_{0.95}(2x+2,\ 2n-2x)} \qquad (9)$$

where $F_r(n_1, n_2)$ is the 100 $r^{th}$ percentile of F-distribution with $n_1$ numerator and $n_2$ denominator degrees of freedom.

TABLE 3: AN EXAMPLE OF A TEST SEQUENCE PERFORMED ON A SOLID ROCKET, ITS RESULTS AND RELIABILITY COMPUTATION USING D. LLOYD'S METHOD

| Test no. (N) | Months of testing* | Results | Value of failure $f = 1 - (1-\gamma)^{1/n}$ | | | | | $\Sigma f$ | $R = 1 - \Sigma f/N$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ | | | |
| 1 | 0 | S | | | | | | 0.000 | 1.000 | Successful test |
| 2 | 3 | S | | | | | | 0.000 | 1.000 | Successful test |
| 3 | 5 | F | 1 | | | | | 1.000 | 0.667 | Failure mode, $f_1$ case burnthrough |
| 4 | 8 | S | 1 | | | | | 1.000 | 0.750 | Successful test |
| 5 | 11 | S | 0.900 | | | | | 0.900 | 0.820 | $f_1$ corrected, internal installation added, success |
| 6 | 12 | S | 0.684 | | | | | 0.684 | 0.886 | Successful test |
| 7 | 13 | S | 0.536 | | | | | 0.536 | 0.923 | Successful test |
| 8 | 14 | F | 0.438 | 1 | | | | 1.438 | 0.820 | Failure mode, $f_2$ TVA failure |
| 9 | 16 | S | 0.369 | 1 | | | | 1.369 | 0.848 | TVA not tested |
| 10 | 18 | S | 0.319 | 0.900 | | | | 1.219 | 0.878 | Successful test of TVA fix |
| 11 | 20 | F | 0.280 | 1 | 1 | | | 2.280 | 0.793 | Failure mode $f_2$ recurs, $f_3$ |
| 12 | 21 | S | 0.250 | 1 | 1 | | | 2.250 | 0.812 | TVA not tested |
| 13 | 23 | S | 0.226 | 0.900 | 0.900 | | | 2.026 | 0.844 | Successful test of 2nd TVA fix |
| 14 | 25 | S | 0.206 | 0.684 | 0.684 | | | 1.574 | 0.888 | Successful test |
| 15 | 28 | S | 0.189 | 0.536 | 0.536 | | | 1.261 | 0.916 | Successful test |
| 16 | 29 | F | 0.175 | 0.438 | 0.438 | 1 | | 2.051 | 0.872 | Spec. violation, $f_4$ |
| 17 | 30 | F | 0.162 | 0.369 | 0.369 | 1 | 1 | 2.900 | 0.829 | 2nd spec violation, $f_5$ |
| 18 | 32 | S | 0.152 | 0.319 | 0.319 | 0 | 0 | 0.790 | 0.956 | Spec. change eliminates $f_4$, $f_5$ |
| 19 | 32 | S | 0.142 | 0.280 | 0.280 | 0 | 0 | 0.702 | 0.963 | Successful test |
| 20 | 33 | S | 0.134 | 0.250 | 0.250 | 0 | 0 | 0.634 | 0.968 | Successful test |
| 21 | 35 | S | 0.127 | 0.226 | 0.226 | 0 | 0 | 0.579 | 0.972 | Successful test |
| 22 | 37 | S | 0.120 | 0.206 | 0.206 | 0 | 0 | 0.532 | 0.976 | Successful test |
| 23 | 39 | S | 0.114 | 0.189 | 0.189 | 0 | 0 | 0.492 | 0.979 | Successful test |
| 24 | 40 | S | 0.109 | 0.175 | 0.175 | 0 | 0 | 0.459 | 0.981 | Successful test |
| 25 | 42 | S | 0.104 | 0.162 | 0.162 | 0 | 0 | 0.428 | 0.983 | Successful test |

* Number of months after start of test program, not length of test.

Notes: Test no. 4: failure from test no. 3 ($f_1$) is not yet diminished because corrective action is not implemented until test no. 5; $f_1$ continues to diminish in all subsequent tests since it does not recur.

Test no. 9: failure from test no. 8 ($f_2$) is not diminished because the thrust vector actuator (TVA) subsystem is not "hooked up" until fix is implemented and successfully tested in test no. 10.

Test no. 11: failure from test no. 8 ($f_2$) recurs; therefore, fix implemented in test no. 10 is not considered successful, and both TVA failures are reinstated as full failures.

Test no. 12: TVA is not tested while failure mode is undergoing engineering analysis, therefore, $f_2$ and $f_3$ are not diminished;

Test no. 13: successful test of new TVA fix applies to both failures ($f_2$, $f_3$); therefore, values of both failures are diminished. TVA failure does not recur in the remainder of the example and, therefore, both failure values continue to diminish.

Test no. 16: small performance anomaly occurs; however, it is outside current specification limits and, therefore, must be considered a failure ($f_4$).

Test no. 17: same as test no. 16 ($f_5$).

Test no. 18: Corrective action for $f_4$ and $f_5$ is to change specifications/conditions (with customer approval). With this change, tests 16 and 17 become "non-failures" and $f_4$ and $f_5$ immediately become zero.

Test nos. 19-25: all are successful, demonstrating a lower probability of failure for $f_1$, $f_2$ and $f_3$ failure modes.

For a complete discussion of this methodology, see Appendix A.3.

2.2 2 D. Lloyd's Methodology (Taken from Reference 14)

D. Lloyd developed a method for estimating and forecasting reliability from attribute data, using the binomial model, when reliability requirements are very high and test data are limited. Integer data—specifically, numbers of failures—are converted, using this approach, into non-integer data. The rationale is that when engineering corrective action for a failure is implemented, the probability of recurrence of that failure is reduced; therefore, such failures should not be carried as full failures in subsequent reliability estimates. The reduced failure value for each failure mode is the upper limit on the probability of failure based on the number of successes after engineering corrective action has been implemented. Each failure value is less than one and diminishes as successes continue. These numbers replace the integral numbers (of failures) in the binomial estimate.

In Lloyd's research, this method of reliability estimation was applied to attribute data from the life history of a previously tested system, and a reliability growth equation was fitted. It was then "calibrated" to allow for reliability projections to be developed for a new similar system. In this way, the model allows for management to discern early on whether the system's ultimate reliability requirement will be met and, if so, when is it likely to be achieved. By comparing current estimates of reliability with the expected value computed from the model, a reliability growth forecast can be obtained by extrapolation.

An example application of Lloyd's method to a solid rocket program is shown in Table 3. As can be seen, the methodology predicts a significantly higher success ratio (.983 vs .80) than would be obtained without considering growth.

2.2.3 Curve Fitting (Polynomial)

Polynomial trends are of the form

$$Y = A + BX + CX^2 + DX^3 + \ldots + JX^k$$

The straight line is a special case, having only the first two terms on the right of the equality sign. With three terms on the right, the polynomial is of quadratic form, and so forth. Typical forms are shown in Figure 3. Generally speaking, it is unwise to fit a high-degree polynomial to the data because doing so almost assures the mixing of trend and cycle. Also, a glance at the figure below will show that none of the polynomials, other than the straight line, can be extended or projected very far without going off the page. Keep in mind that only a portion of the curve is used to represent the trend.

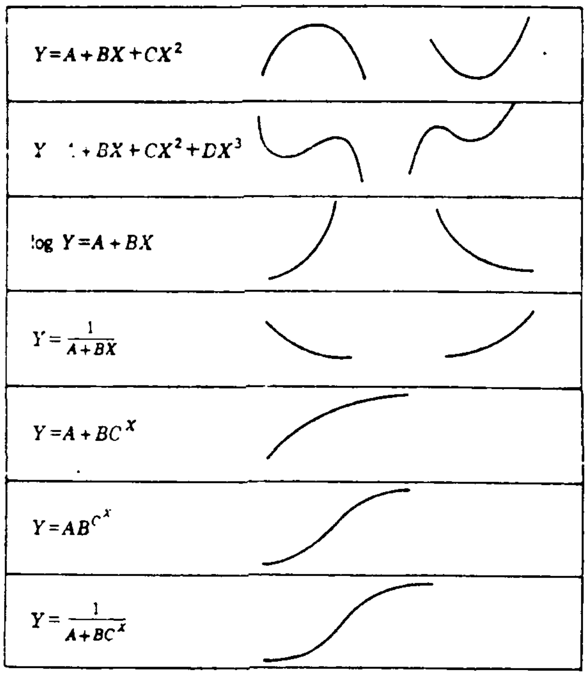



Figure 3. Typical forms of some trend equations.

Of course, a polynomial can be forced to fit the data quite closely by adding enough terms. A well known theorem in algebra states that a polynomial of degree $k$ can be passed through $k+1$ points on a plane. Accomplishing this, or anything near to it, does not contribute any information about trend. This becomes evident when it is recalled that 1 degree of freedom is lost for error for every parameter that is estimated from the data. Thus, if there are $n$ observations and $n$ degrees of freedom are lost in fitting a polynomial of degree $n$-1, 0 degrees of freedom left for error.

All polynomials can be fitted utilizing the method of least squares.

2.2.4 Bayesian (Reference 15)

Suppose a propulsion system is being built with a 0.95 reliability requirement at the 90% confidence level. The system goes through a number of tests: component, environmental, subsystem, system, extended time, etc. There are failures which are corrected (permanently, it is hoped). A final configuration is attained. It is also assumed that the project is at least 50% sure that a 0.95 reliable system has been achieved If thirteen tests are run with no failures, has the 0.95 requirement been met? The classical binomial approach (see section 2.2.5) would indicate that the requirement has not been met.

This problem is typical of today's work in the aerospace industry: few systems, few tests, compressed schedules and high reliability requirements and costs. The limited number of samples for test permit no failures since even one failure would imply an intolerably high failure rate. Indeed, all "hi-rel" programs have "failure recurrence prevention" systems. All failures are "fixed" and "closed". These activities, in effect, imply that at time of "buy off," no failures should occur on qualification or demonstration tests. Hence, any solution to the reliability demonstration problem should, as a practical matter, address itself to zero failures and few trials.

Bayes Theorem, in the continuous case, states:

$$\text{Prob}\ (R \le p \le 1 \mid r) = \frac{\int_R^1 g_r(r \mid p)\, w(p)\, dp}{\int_0^1 g_r(r \mid p)\, w(p)\, dp} \qquad (1)$$

Here, $R$ = lower (Bayesian) confidence limit of the true reliability, $p$;

$r$ = observed number of failures in $n$ trials;

$g_r(r \mid p)$ = the conditional probability density function of $r$ given $p$; and

$w(p)$ = the a priori frequency function of $p$.

In the binomial case,

$$g_r(r \mid p) = \binom{n}{r} p^{n-r} q^{r} \qquad (2)$$

Here $\binom{n}{r}$ = The number of combinations of $n$ things taken $r$ at a time;

$$q = 1 - p$$

It is assumed that the engineer is capable of assigning a probability, P (degree of belief) to the event that the required reliability, or more, has been attained prior to test. It is also assumed that this prior belief declines linearly to zero at $P = 0$ and $P = 100\%$.

Thus, w(p) takes the form of the triangle distribution as follows:

$$w(p) = \frac{2(1-P)\,p}{R^2} \quad \text{for } 0 \le p \le R \qquad (3)$$

$$w(p) = \frac{2P(1-p)}{(1-R)^2} \quad \text{for } R \le p \le 1 \qquad (4)$$

Here, P = prior probability of having the required reliability, R.

That w(p) does have the proper values can be seen by obtaining the required heights at R and multiplying these frequencies by the bases R and (1-R) of the triangles of (3) and (4). Then for the left hand interval, (0, R), we have at $p = R$,

$$w(R) = \frac{2(1-P)\,R}{R^2} = \frac{2(1-P)}{R}$$

Area over $\quad (0,R) = \dfrac{R \cdot w(R)}{2} = 1 - P$

Similarly at p = R for the right hand interval, (R, 1), we have

$$\text{Area over} \quad (R,1) = \frac{(1-R)\,w(R)}{2} = \frac{(1-R)\,2P(1-R)}{2(1-R)^2} = P$$

Note: The discontinuity at R is of probability measure zero.

Inserting (2), (3), and (4) in (1) yields, after cancellation and simplication,

$$\Pr ob(R \le p \le 1) = \cfrac{1}{1 + \cfrac{(1-P)(1-R)^2 \int_0^R p^{n-r+1} q^r \, dp}{(P)(R)^2 \int_R^1 p^{n-r} q^{r+1} \, dp}} \qquad (5)$$

Figure 4 graphically displays equation (5). <u>Note that in this case, thirteen tests with zero failures are adequate to demonstrate a reliability of 0.95 at 90% confidence</u> (given a 0.5 on the Bayesian Prior scale).

While there can be no doubt that Bayesian methods, as can be seen from this example, can provide significant test reduction to demonstrate a reliability requirement, performing the analysis requires the development of a prior distribution which is, at least to some degree, subjectively based. Also, Bayesian approaches are highly sensitive to the prior distributions used. If no meaningful estimate of the prior probability of success can be made, none of the above conclusions apply. Particularly, one must be wary of consistent optimism or pessimism when records of success do not support the prior probabilities.

For example, if optimism about a new design is guarded and feasibility tests are few or non-existent, then the analysis is driven towards a rectangular prior (equally probable prior intervals), and the results are just as unfavorable (in terms of the large number of tests required) as they are for the binomial distribution. In other words, since one cannot be over 0.5 on the prior scale, 11 tests are required with zero failures to be .90 reliable at 90% confidence, the same as the binomial. This defeats the purpose of the Bayesian approach.

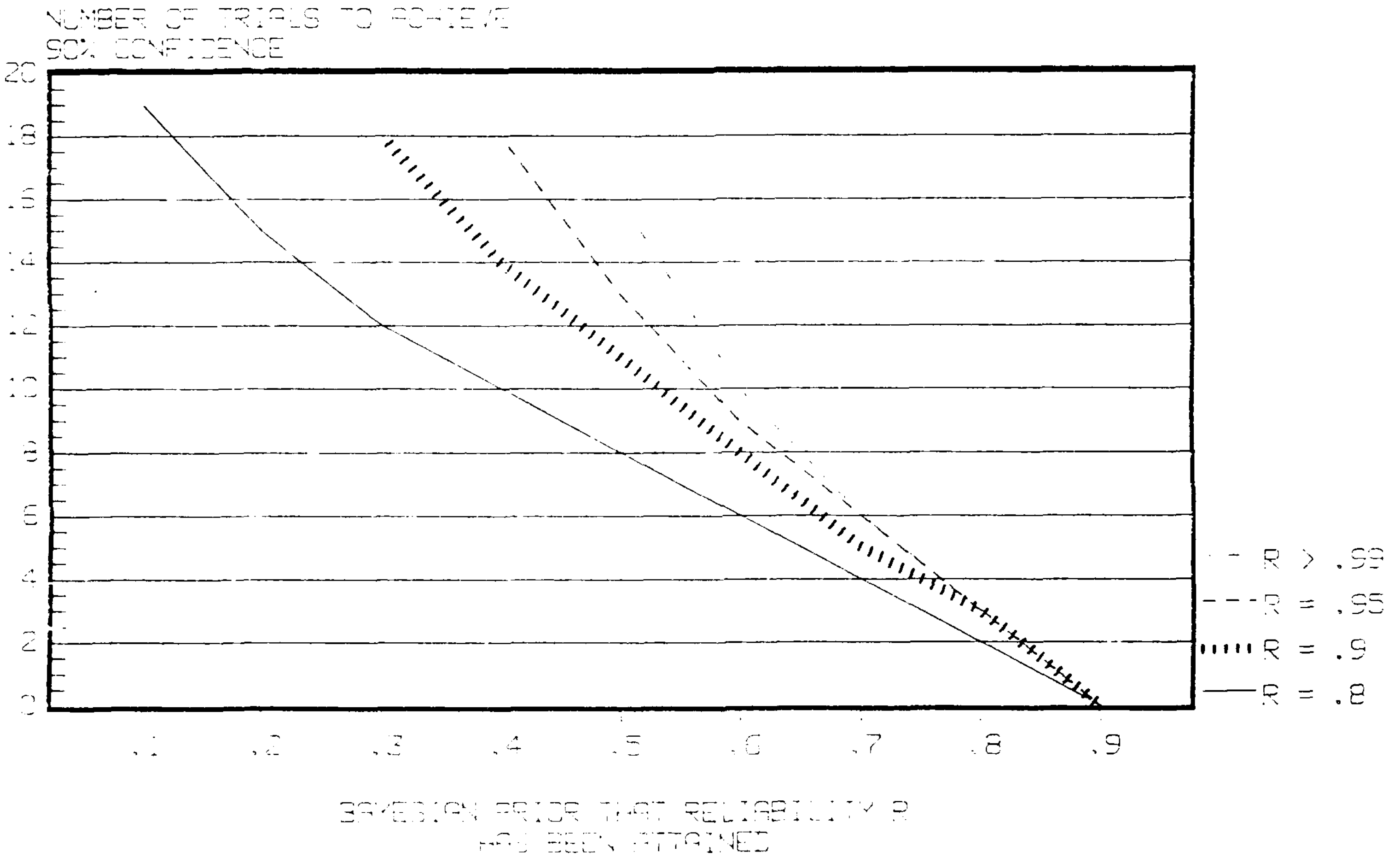



Figure 4. Number of trials with 0 failures to achieve 90% confidence that reliability R has been attained when a Bayesian prior is used.

The following are two examples of applying Bayes Theorem.

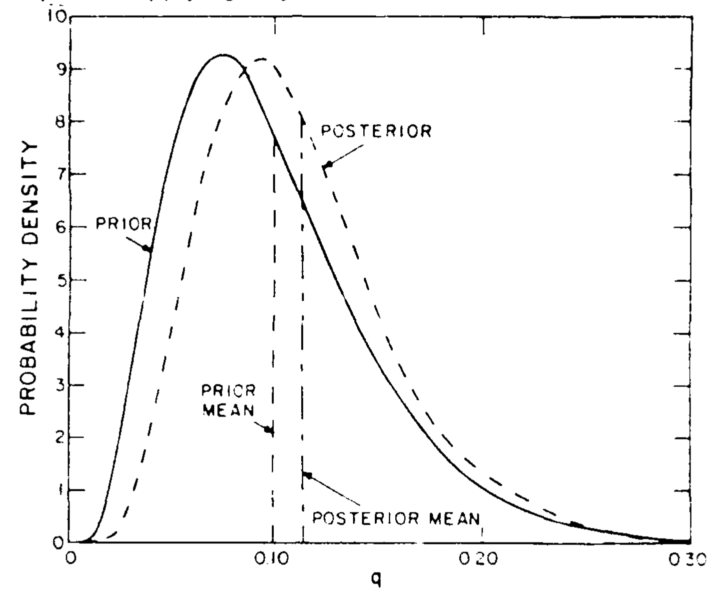



Figure 5. The prior and posterior distribution in example 1.

Figure 5 portrays the results of applying Bayes Theorem to estimate the unreliability of the material (LX-13 or Exter) which is an extrudable high explosive used in a variety of systems (Ref. 15). As can be seen, the posterior distribution is not much different from the prior distribution. In this case, the present observed data (failure numbers, test numbers) is relatively small compared with the previous data, and the prior distribution is given great weight in the final unreliability estimation.

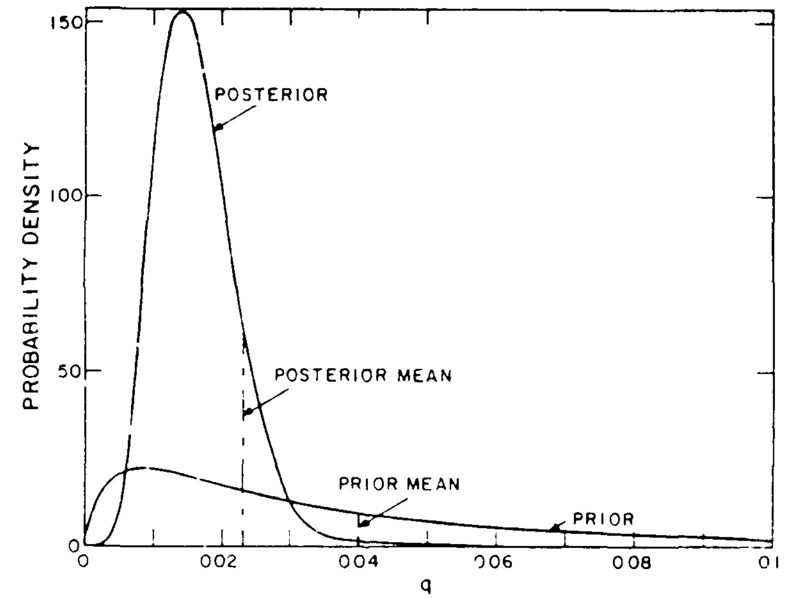



Figure 6. The prior and posterior distribution in example 2

Figure 6, on the other hand, portrays the results of applying Bayes Theorem to estimate the annual pump unreliability for pressurized water reactor (PWRS) in commercial operation in the United States (Ref. 15). It is observed that the posterior distribution is much less diffuse than the prior distribution as a consequence of incorporating the obeserved data. In this case, the present observed data set is large and it is given much weight in the final estimation.

2.2.5 Classical Binomial Approach

The "traditional" approach to reliability demonstration in a go-no-go type environment is the well known Binomial distribution.

Stated mathematically the Binomial Distribution is as follows:

$$\sum_{X=S}^{N} \binom{N}{N-X} R^{X} (1-R)^{N-X} = 1-C, \text{ if } N \leq S \leq 0$$

where;

S = number of successful start tests

N = number of trials

R = reliability

C = Confidence level

where it is assumed that

- Trials or tests are independent
- Each trial results in success or failure
- The reliability (probability of success) of each system is the same on each trial
- The number of tests is fixed in advance of the demonstration test

Note that it would take 45 tests with no failures to demonstrate 0.95 reliability at 90% confidence (see Table 4).

TABLE 4: BINOMIAL TABLES

**Number of Tests Without Failure Vs Reliability and Confidence Level**

| Reliability (R) | Confidence Level, Percent | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | 60 | 70 | 75 | 80 | 85 | 90 | 95 | 97.5 | 99 | 99.5 | 99.9 |
| 0.999999 | 693150 | 916290 | 1203970 | 1386290 | 1609440 | 1897120 | 2302590 | 2995730 | 3688889 | 4605170 | 5298320 | 6907760 |
| 0.99999 | 69315 | 91629 | 120397 | 138629 | 160944 | 189712 | 230259 | 299573 | 368889 | 460517 | 529832 | 690776 |
| 0.9999 | 6932 | 9163 | 12040 | 13863 | 16094 | 18971 | 23026 | 29957 | 36889 | 46052 | 52983 | 69078 |
| 0.999 | 693 | 916 | 1204 | 1386 | 1609 | 1897 | 2303 | 2996 | 3689 | 4605 | 5298 | 6908 |
| 0.998 | 347 | 458 | 602 | 694 | 805 | 949 | 1152 | 1493 | 1845 | 2303 | 2650 | 3454 |
| 0.997 | 231 | 305 | 401 | 462 | 537 | 632 | 768 | 999 | 1230 | 1535 | 1766 | 2303 |
| 0.996 | 173 | 229 | 301 | 346 | 401 | 473 | 575 | 747 | 920 | 1149 | 1322 | 1723 |
| 0.995 | 138 | 183 | 241 | 277 | 321 | 379 | 460 | 598 | 737 | 920 | 1058 | 1379 |
| 0.994 | 115 | 152 | 201 | 230 | 267 | 315 | 383 | 498 | 613 | 765 | 880 | 1148 |
| 0.993 | 99 | 130 | 174 | 198 | 229 | 270 | 328 | 427 | 526 | 657 | 755 | 985 |
| 0.992 | 86 | 114 | 150 | 173 | 200 | 236 | 287 | 373 | 460 | 574 | 660 | 860 |
| 0.991 | 77 | 101 | 134 | 153 | 178 | 210 | 255 | 332 | 408 | 510 | 586 | 764 |
| 0.99 | 69 | 92 | 120 | 138 | 160 | 188 | 229 | 298 | 367 | 459 | 527 | 688 |
| 0.98 | 34 | 45 | 60 | 69 | 80 | 94 | 114 | 149 | 183 | 228 | 263 | 342 |
| 0.97 | 23 | 30 | 40 | 45 | 53 | 62 | 76 | 99 | 121 | 151 | 174 | 227 |
| 0.96 | 17 | 23 | 30 | 34 | 39 | 46 | 57 | 74 | 91 | 113 | 130 | 170 |
| 0.95 | 14 | 18 | 24 | 27 | 31 | 37 | 45 | 58 | 72 | 90 | 103 | 135 |
| 0.94 | 11 | 15 | 20 | 22 | 26 | 31 | 37 | 49 | 60 | 75 | 86 | 112 |
| 0.93 | 10 | 13 | 17 | 19 | 22 | 26 | 32 | 42 | 51 | 64 | 74 | 96 |
| 0.92 | 9 | 11 | 15 | 17 | 19 | 23 | 28 | 36 | 45 | 55 | 64 | 83 |
| 0.91 | 8 | 10 | 13 | 15 | 17 | 20 | 25 | 32 | 39 | 49 | 57 | 74 |
| 0.9 | 7 | 9 | 12 | 13 | 15 | 18 | 22 | 29 | 35 | 44 | 51 | 66 |
| 0.8 | 3 | 4 | 6 | 6 | 7 | 9 | 11 | 14 | 17 | 21 | 24 | 31 |
| 0.7 | 2 | 3 | 4 | 4 | 5 | 6 | 7 | 9 | 11 | 13 | 15 | 20 |
| 0.6 | 2 | 2 | 3 | 3 | 4 | 4 | 5 | 6 | 8 | 9 | 11 | 14 |
| 0.5 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 5 | 6 | 7 | 8 | 10 |

## 2.3 Baseline Reliability Enhancement Methodology Identification

### 2.3.1 Proposed Infrastructure Controls Affecting Reliability

Figure 7 illustrates how various activities related to the categories of design, manufacturing, test, transportation, storage and operation can have an effect on reliability. Each category has listed underneath it examples of reliability enhancing technique and tools. They represent a cross section of ideas accumulated during the site visits of Task 1. Some of the techniques are well known and proven, such as reliability predictions/trade offs. Others are not, such as operating characteristic curves vs. reliability.

The following is a discussion of proposed infrastructure controls intended to enhance reliability. The discussion is divided into quantitative and qualitative approaches followed by a discussion of risk assessment as a decision making tool.

<u>Quantitative Approaches</u> - Analysis of Historical Data (See Section 2.2), PRACA/FRACA Trending - In order for a Problem/Failure Reporting and Corrective Action system to be suitable for mathematical trending, basic changes must take place in the way information is recorded and tracked (see Section 1.1.3.2). These changes include as a minimum:

- Recording total operating times on failed as well as unfailed components
- Total number of cycles or trials (both successes and failures)
- Inclusion of reports of all component malfunctions, even those which were non-catastrophic and occured on non-critical components.

<u>Operating Characteristic Curves Correlated to Failure Modes/Rates</u> - The example that follows illustrates one method of connecting defect rates from Q.C. sampling plans to reliability calculations for hardware. Although this example is for solar array calculations, there is every reason to believe that a similar approach could be used for propulsion systems.

- Data

- If entire population had random defect rate of 0.65%, one would expect to reject 10% of lots due to the randomness of sampling process. Figure 12 (page 73) illustrates the use of MIL-STD-414 for the purpose of determining the 10% reject rate. The 0.65% defect rate corresponds to a 90% confidence for the lots expected to be accepted or, conversely, 10% are expected to be rejected. Assume that the MIL-STD 414 plan has thus far rejected 58/434 = 13.4% of lots

- This result is indicative of non-homogeneous population wherein some lots are worse than 0.65% and therefore have a higher probability of being rejected; clustering of bad lots is also indicative of non-homogeneous population

- Thus, residual defect rate in the accepted lot subpopulation will be less than 0.65% per test; assume observed rate in lots accepted to date is 0.65%

- For purposes of an example, consider estimating solar array reliability, a failure probability of 0.25%, will be assumed for each interconnect over the course of the three year mission (conservative)
- Each quarter string consists of an average quantity of 39 cells
- Power margin allows subsystem to accept 22 quarter string failures in each of two sets of 992 quarter strings

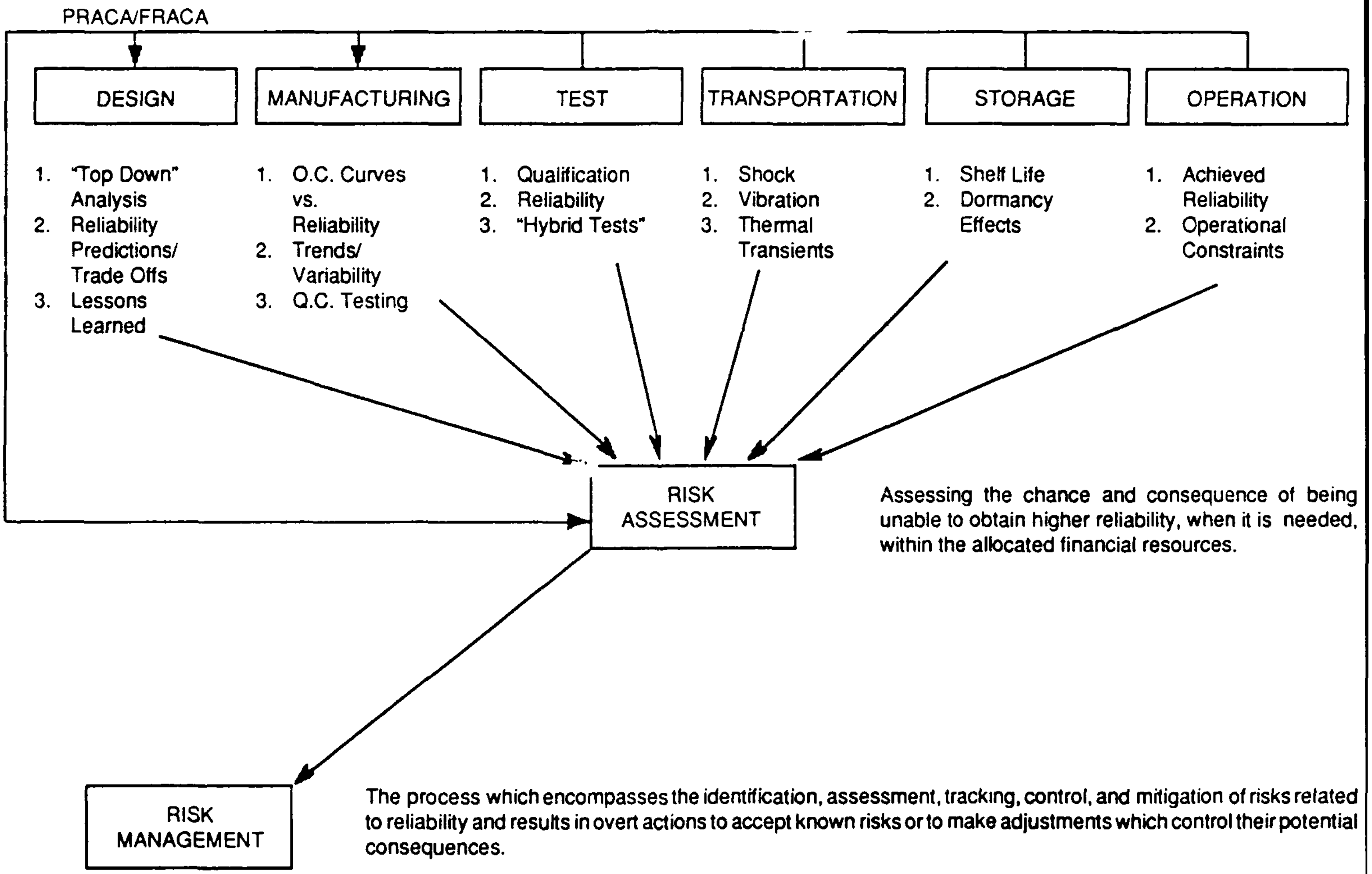



Figure 7. Infrastructure controls proposed to enhance reliability.

• Two of four interconnects on a cell are pulled as part of sampling test; failure probability per pull estimated as 0.25%; two tested interconnects are from either end of cell; data from immediately adjacent interconnects is not available.

- Correlation between pull strength values from same cell analyzed and found to be .38 for all lots tested, .54 for the ten "bad" lots tested, and .32 for "unknown" lots; value would be somewhat smaller yet if attention were restricted only to lots accepted by sampling process

- Correlation of .32 means that knowing the strength of one interconnect helps one predict the strength of a second interconnect on the same cell (.32 .32) = .10 or 10% more accurately than one could predict it without knowing the first value; the square of the correlation is known in statistics as the coefficient of determination.

• Probability of both interconnects failing is:

- PR (first failing) * PR (second failing/first fails);

- PR (A/B) read as probability of A given that B is known to occur

- If totally independent, PR (Second Failing/First Fails) = 0.0025

- If totally dependent, PR(Second Failing/First Fails)=1.0

- Since the 10% factor developed above measures the strength of the dependency which exists, it may be used to interpolate between .0025 and 1.0 to estimate PR (Second Failing/First Fails)

(1.0 - .0025) *.10 + .0025 = .10225

• Probability of two interconnect failures out of two on same cell is thus estimated at .0025 * .10225 = .00026

• Since adjacent interconnects are probably somewhat more correlated than those at either end of cell, and since degree of correlation is not known, if we assume that interconnects fail at both ends of the cell, then the cell will fail totally . Using this assumption will, of course, produce somewhat of an overestimate of probabilities. This overestimate is, however, small compared to the effect being observed.

- This means we will estimate the mission failure probability for a cell to be .00026.

- This equates to a cell failure rate of:

-LN(1-.00026)/26298 = 9.9E-9/HR

- A quarter string with 39 cells will thus have a failure rate due to interconnects conservatively estimated at 39 * 9.9E-9 or 386E-9/HR

• The impact of this new cell failure mode on the array is to change the failure probability from $6.25 \times 10^{-6}$ to $6.21 \times 10^{-4}$, an approximate two order of magnitude change.

Qualitative Approaches - Product Design FMEAs - Although Product Design FMEAs are not unheard of in the aerospace industry, very few companies perform them. In essence, product design FMEAs are structured to identify sources of common cause failures (sometimes called "coverage factors" or "correlation factors" by propulsion manufacturers).

Although the following product design description is directed towards electrical/electronics components, a similar approach could be used for propulsion system components.

Product design Failures Modes and Effects Analyses (FMEAs) are performed to verify that hardware reliability and integrity is maintained when electrical/mechanical designs are implemented as hardware during the product design phase. This tvpe of analysis is typically done between PDR and CDR after drawings become available, but before they are released.

This analysis is particulaly appropriate for examining areas where redundant or backup paths are in proximity.

When redundancy is implemented by using separate units, there is generally no need to do a product design FMEA inside each unit. However, this may not be true for high energy systems such as propulsion. In either case, unit external interfaces, e.g., input/output cross-straps, should be examined. Example: product design criteria are listed below. Results are documented on Product Design FMEA Forms. Where negative findings occur, remedial action is recommended. Adverse conditions are to be justified at design audits.

The following Reliability Criteria for Product Design are applied in performing product design FMEAs for printed circuit boards, connectors, and wiring interfaces:

Cabling, Hardnesses, and Wire Bundles

a) Assure that fault isolation exists.

b) The routing of all wire bundles shall be such that all possible locations where wire pinching or chaffing could occur are eliminated to prevent shorts to ground or shorts to different voltage or signal source.

c) Assure that the design prevents screw threads from coming into contact with wire/leads during assembly.

d) Provide for special sleeving where wire routing is adjacent to sharp edges.

e) Prevent excessive pinching of wires by cable clamps by properly dressing bundle and sizing clamps.

f) Spot bond or tie wire adjacent to standoffs and with reasonable distance between supports such that loads/joints are not degraded during exposure to vibration or shock.

g) No single wires or single solder joints shall be system single point failures.

Connectors

a) Similar connectors on a unit shall be keyed, color-coded, or have other mismating protection.

b) Physically separate power and ground pins.

c) Different polarity signals shall not have adjacent pin assignments (Vis.; +28Vdc, -15Vdc).

d) Sensitive low level signals should have pin assignments physically separated from high level power, high level signals, or ungrounded returns This should also apply to grounds.

e) Critical power or signal lines shall not have adjacent pin assignments.

f) Redundant power or signal lines shall not have adjacent pin assignments.

g) Review pin and slip ring assignments to assure that shorts between adjacent pins will not result in single point failures.

h) No single connector pin shall be a system single point failure.

Printed Circuit Boards

a) Review that redundant paths are kept physically separated as much as possible.

b) Traces carrying heavy current loads shall be verified as having adequate load carrying capacity per MIL-STD-275.

c) There shall be no open daisy chains for power or ground paths.

d) Sufficiency in the spacing between traces depends on trace voltages and conformal coating provisions. These should be reviewed against Standard Engineering Design Systems to confirm that trace-to-trace shorts will not occur.

e) A grounding circuit trace leading to board edge common ground should be filleted at the lead-in line to prevent development of cracks in circuit conductors.

f) Check that redundant paths don't go through the same piece part, e.g., a dual transistor or quad IC.

g) If there are any single PC traces or plated-thru-holds where an open would result in a system single point failure, hardwire should be added.

h) Care shall be taken to assure that high heat generating parts are isolated from cirtical signal paths (via distance/shielding) to preclude burnout of PC traces, etc.

i) Ensure that solder joints are inspectable. Avoid soldering flush-mounted parts near heat sinks or other items which might make the presence of solder balls undetectable.

j) Ascertain that the block diagram or schematic-illustrated redundancy is reflected by the wiring diagram.

k) Assure that solder reflow practices for boards (or within parts) will not reflow or degrade prior connections.

l) Handling and installation loads for cards and assemblies must be reviewed to ensure that stresses imposed on joints are within their load-carrying capability.

m) PC traces and wiring should be physically separated such that a fault is isolated and will not cascade to redundant or adjacent elements.

n) Verify that PC boards which contain redundancy or cross-strapping elements are adequately protected against shorts to ground (internal and external to the board) which could represent a system single point failure.

o) Plated-thru-holes shall have an aspect ratio (board thickness to hole diameter) or no greater than 3 to 1.

**Function Expected* or Output Required**

| | | | 0 | 1 | 2 | 3 | 4 | 5 . . . n |
|---|---|---|---|---|---|---|---|---|
| FUNCTION PROVIDED OR RESULTING OUTPUT | (WRONG TYPE) | 0 | | | | | | |
| | | 1 | | | | | | |
| | | 2 | | | | | | |
| | | 3 | | | | | | |
| | | 4 | | | | | | |
| | | 5 . . . n | | | | | | |
| | (WRONG QUALITY) | More of (n+1) | | | | | | |
| | | Less Than (n+2) | | | | | | |
| | | As Well As (n+3) | | | | | | |
| | | Part of (n+4) | | | | | | |
| | | Reverse (n+5) | | | | | | |
| | | Other Than (n+6) | | | | | | |

*Obtained from a clear, concise, unambiguous set of Engineering functional descriptions

Figure 8. Top down matrix.

Manufacturing Control FMECAs (See Appendix B: MCDAC Trip report) - In the case of the manufacturing control FMECA, the FMECA should be conducted incrementally by reliability engineering during the design phase to identify single point failure modes. The FMECA should be used in the Critical Item Control process by identifying critical items and the causes of critical failure modes. Proper design controls would then be implemented for each critical item and can be verified by a Manufacturing Control Plan. FMECAs should be supplemented with failure history prior to FMECAs of related designs and, along with the failure history, should be made available to designers.

A manufacturing Control Plan should contain as a minimum the following task:

- Identify flight critical items (FCIs) using FMECAs
- Determine flight critical characteristics for each FCI
- Identify specific manufacturing methods for each FCI
- Prepare Manufacturing Flow Chart and annotate
- Identify Process Control for each select manufacturing method
- Identify test and/or inspection methods for each select manufacturing method

Top Down Analysis (L. Booth Method) - The most common criticism of FMEAs is the possibility that not all conditions causing system anomalies, malfunctions or failures are attributable to inherent component failures.

One way to address this concern is by conducting a "Top Down" analysis. A Top Down analysis is conducted by accomplishing the following tasks:

- Obtain a clear, concise, unambiguous set of engineering functional descriptions
- Form a matrix as shown on Figure 8
- For each intersection (square) on the matrix, describe the system condition (i.e., 0 = nominal thrust, n+6 (other than) = wrong direction). Therefore, (0, n+6) means correct thrust, wrong direction. The square (0,0) indicates correct nominal thrust was required and correct nominal thrust was delivered.
- Each square of the matrix is a potential "Top Event" (undesirable condition).
- Explore each top event (using fault trees, event trees or similar techniques) until all conditions leading to the top event have been exhausted.

Risk Assessment (reference Figure 7) - Risk assessment can be characterized as follows:

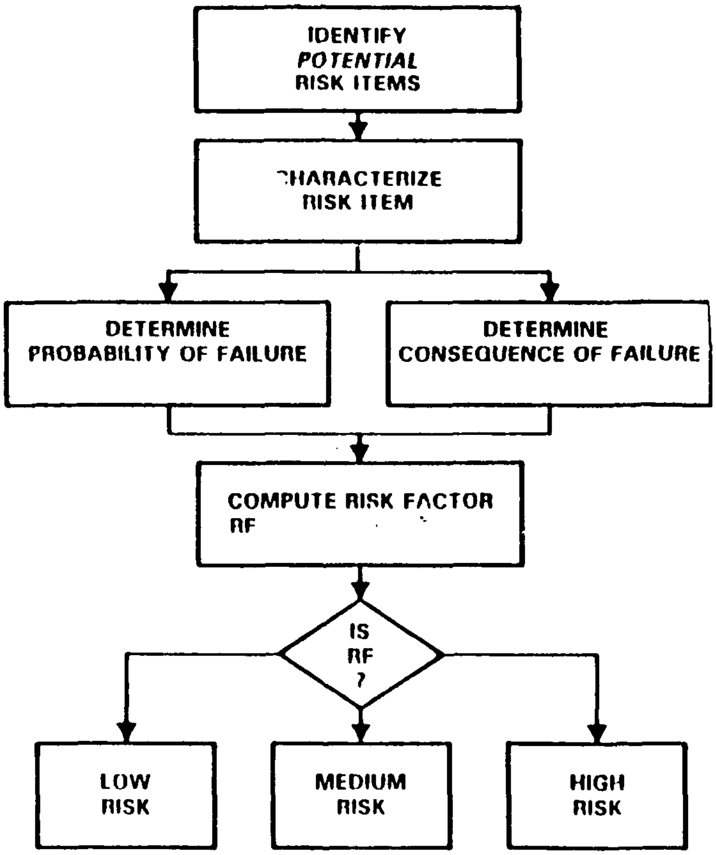
- Risk assessment is the process for estimating the risk associated with a particular alternative course of action
- Risk assessment considers probability of failure and consequence of failure as they relate to technical performance, schedule, and cost

Where

Risk is the probability and consequence of not achieving some defined program goal and is a function of:

- Probability of failure
- Consequence of failure
  - Increased Cost
  - Extended schedules
  - Reduced performance

Risk assessment involves these steps indicated in the following diagram:




Where risk levels are defined as:

High The problem is obvious and there is a high probability of failure to meet reliability, performance, schedule or cost objectives. Monitoring and control must be rigorous, with frequent update of risk status. A fall-back or alternative system or plan is mandatory.

Medium - The problem is identifiable and would impact program reliability, performance, schedule, or costs. The probability of occurence is high enough to require close control of all contributing factors, establishing of risk management milestones, and an acceptable fall-back position.

Low - The problem is identifiable and would impact program objectives, but the probability of occurrence is low as to cause no concern other than normal monitoring and control.

2.3.2 Risk Management

Risk management is the process which encompasses the identification, assessment, tracking, control and mitigation of risks related to reliability and results in overt actions to accept known risks or to make adjustments which control their potential consequences.

Risk assessment assesses the chance and consequence of being unable to obtain higher reliability, when it is needed, within the allocated financial resources.

Establishing Factors - In order to assess and manage risk, factors must be established based on technical risks. Factors can be characterized by using the two following matrices (Figures 9 and 10).

Assessing Economic Risk - Given the information of sections 2.3.1.3 and 2.3.2.1 are available, the most efficient way to assess economic risk is to use an established model tailored to the rocket industry. The model accounts for both production and operational processes that would be impacted by unreliability. Additional economic modeling of the cost of unreliability to customer communities is essential to gain a meaningful estimate of economic risk. Economic models must evaluate the actual cost of finite activities required to reduce risk by finite amounts.

In the case of launch vehicles, most individuals recognize the direct costs of unreliability such as residual hardware that is scrapped due to more rigorous inspections or redesign effort. The incorporation of additional quality control that slows production rates and operational process timelines while increasing the total amount of personnel and facilities that are required to support the vehicle is a more subtle cost effect of unreliability. The largest cost is related to payload communities that suffer direct losses in the form of lost hardware and higher insurance rates, as well as launch schedule backlog effects that result in program slippage that has cost of money and cost of storage implications. Actual costs of unreliability are difficult to estimate accurately, but the costs may be bounded from documented historical events that give a real estimate of cost risk exposure.

Perhaps the greatest single "cost" of unreliability can be related to loss of strategic capability at critical time windows. For the military, this may be the absence of reconnaisance capability during evolving international crises or a less capable navigation or communications environment for operations. For the private sector, the strategic loss may be in the form of lost opportunity to penetrate specific markets at advantageous time windows. Unreliability also results in loss of national stature and a hinderance in the ability to successfully compete with the international community.

The economic risk of unreliability is but one element of the overall risk assessment. The overall risk is a combination of economic risk, schedule risk, and mission capability risk. In essence, the approach would be to assign relative figures of merit (ranging from 0 to 1) of each of the risk factors of Figures 9 and 10, then compare the summed risk factors against a cost of reducing the overall risk. The program manager can then look at the relative cost benefit of risk reduction investment options that assures ultimate program viability.

| Maturity Factor | | Complexity Factor | | Dependency Factor |
|---|---|---|---|---|
| Hardware | Software | Hardware | Software | |
| Existing | Existing | Simple design | Simple design | Independent of existing system, facility, or associate contractor |
| Minor redesign | Minor redesign | Minor increases in complexity | Minor increases in complexity | Schedule dependent on existing system, facility, or associate contractor |
| Major change feasible | Major change feasible | Moderate increase | Moderate increase | Performance dependent on existing system performance, facility, or associate contractor |
| Technology available, complex design | New software, similar to existing | Significant increase | Significant increase/major increase in a number of modules | Schedule dependent on new system schedule, facility, or associate contractor |
| State of art, some research complete | State of art, never done before | Extremely complex | Extremely complex | Performance dependent on new system schedule, facility, or associate contractor |

**Figure 9. Typical top-level factors contributing to probabilty of failure.**

# Typical Top-Level Factors Contributing to Consequence of Failure

| Technical Factor | Cost Factor | Schedule Factor |
|---|---|---|
| Minimal or no consequences, unimportant | Budget estimates not exceeded, some transfer of money | Negligible impact on program, slight development schedule change compensated by available schedule slack |
| Small reduction in technical performance | Cost estimates exceed budget by 1 to 5 percent | Minor slip in schedule (less than 1 percent), some adjustment in milestones required |
| Some reduction in technical performance | Cost estimates increased by 5 to 20 percent | Small slip in schedule (1 to 10 percent) |
| Significant degradation in technical performance | Cost estimates increased by 20 to 50 percent | Development schedule slip (10 to 30 percent) |
| Technical goals cannot be achieved | Cost estimates increased in excess of 50 percent | Large schedule slip that affects segment milestones or has possible affect on system milestones (greater than 30 percent) |

Figure 10. Typical top-level factors contributing to consequence of failure.

## 3.0 (TASK 3) QUANTIFICATION AND PRIORITIZATION OF METHODOLOGIES

In many cases, there is insufficient information to completely quantify and prioritize the methodologies that have been identified. In other cases they are difficult to prioritize because of the qualitative nature of the methods. In any case, thorough testing of the various methodologies should be the subject of future studies (see recommendations).

### 3.1 Testing of Quantitative Methods

Three areas of study appear to be promising. They are:

- Comparison of the methods of Section 2.2
- PRACA/FRACA Trending
- Connecting Operating Characteristic Curves to Reliability

#### 3.1.1 Comparison of the Methods of Section 2.2

Section 2.2 includes a description of a selected number of quantitative methods intended to indicate reliability growth as well as demonstrating the achievement of a prescribed reliability goal.

Four of the methodologies - Binomial model, Beta-Binomial model (Bayesian Estimation), Lloyd's model and Shen's model for estimating reliabilities of launch vehicles from attribute data are introduced and compared in a preliminary manner.

Binomial Model - The simplest way to estimate the reliabilities of launch vehicles is to use the Binomial model. It is easy to perform the calculations, but a large size sample is required to demonstrate high reliability. The results obtained by applying this model do not account for the reliability growth effect expected during the developmental history of the launch vehicles.

Beta-Binomial Model (Bayesian Estimation) - The Beta-Binomial model is based on the Bayesian Estimation. In this model, several similar components are treated as a single class. The probability p of each component in the class is assumed to be constant but will have different values from component to component [i.e., g(p)]. If the Binomial distribution is used to obtain the probability of K failures in n tests for each component, the conjugate distribution g (p) for the class is the Beta distribution. This model weights the reliability growth effect and can be applied to forecast the reliabilities of launch vehicles. The detailed theoretical analysis can be found in Ref. 19, "Bayesian Reliability Analysis" by Harry F. Martz and Ray A. Waller, 1982. The disadvantage of this model is that it is very difficult to separate the total sample data into several similar components, unless we have the detailed engineering analysis and each failure model at the different periods of the launch vehicle developmental history.

Lloyd's Model (Ref. 14) - In Lloyd's model, the rationale is that when engineering corrective action for a failure is implemented, the probability of recurrence of that failure is reduced; therefore, such failures should not be carried as full failures in subsequent reliability estimates. The failure value for each failure model is assumed to be

$$f = 1 - (1 - \gamma)^{1/n} \qquad (1)$$

where $\gamma$ is the confidence level and n is the number of successful tests after corrective action.

Based on a detailed engineering analysis for each failure mode, the result of failure number for each failure mode can be obtained by solving eq. 1. The final result of the reliability estimation is $R = 1 - \Sigma f/N$, where $\Sigma f$ is the cumulative failure number of all failure modes. N is the test number.

This model weights the growth effect and can be extended to forecast the reliability. For this model one needs to know not only at which launch number the failure occured, but also at which launch number the failure was corrected. The confidence level chosen in eq. 1 directly affects the final results and is difficult to justify. The confidence level for the final result $R = 1 - \Sigma f/N$ is not clear.

Shen's model (Ref. Appendix A.3) - In Shen's model, the reliability Rn of a launch vehicle at the $n^{th}$ launch is obtained as

$$R_n = 1 - U_n = 1 - [F_n/L_n - 2/L_n \sum_{i=1}^{N} (F_i - F_n/L_n \cdot L_i)/N] \quad (2)$$

where $U_n$ is the unreliability at $n^{th}$ launch

$F_n$ is the cumulative failure number at $n^{th}$ launch

$L_n$ is the $n^{th}$ launch number

$F_i$ is the cumulative failure number at $i^{th}$ launch

$L_i$ is the $i^{th}$ launch number.

The term $F_n/L_n$ in eq.2 is the estimated average unreliability at the $n^{th}$ launch. The term

$2/L_n \sum_{i=1}^{N} (F_i - F_n/L_n \cdot L_i)/N$ in eq.2 is the corrective unreliability caused by growth effect.

This model is simple and easy to apply. It weights the growth effect and can be extended to predict the future reliabilities of the launch vehicles. The final results of the model are obtained directly from the collected data in which only the launch numbers at which the failures occured need to be known.

However, since this model does not assume any knowledge of what changes were made subsequent to failures, it does not directly incorporate the effects of engineering analysis and corrective action taken after each failure. For this reason, its reliability growth forecast lags that of Lloyd's method.

From the above analysis of these four methodologies, the Lloyd's model and Shen's model are considered to be the better models for estimating reliabilities of launch vehicles.

Fig.11 illustrates the results by applying Lloyd s and Shen's models to an example from Ref. 1. As we can see, the tendencies of the results for both models are similar, the values of estimating reliability from Lloyd's model are higher then those from Shen's model.

In the present study, based on the collected data, the Shen model is used to estimate the reliabilities for twenty-four U.S. launch vehicles. The growth trends obtained from the model are shown in Figures 11a, and 11b for the Delta and Titan families of launch vehicles.

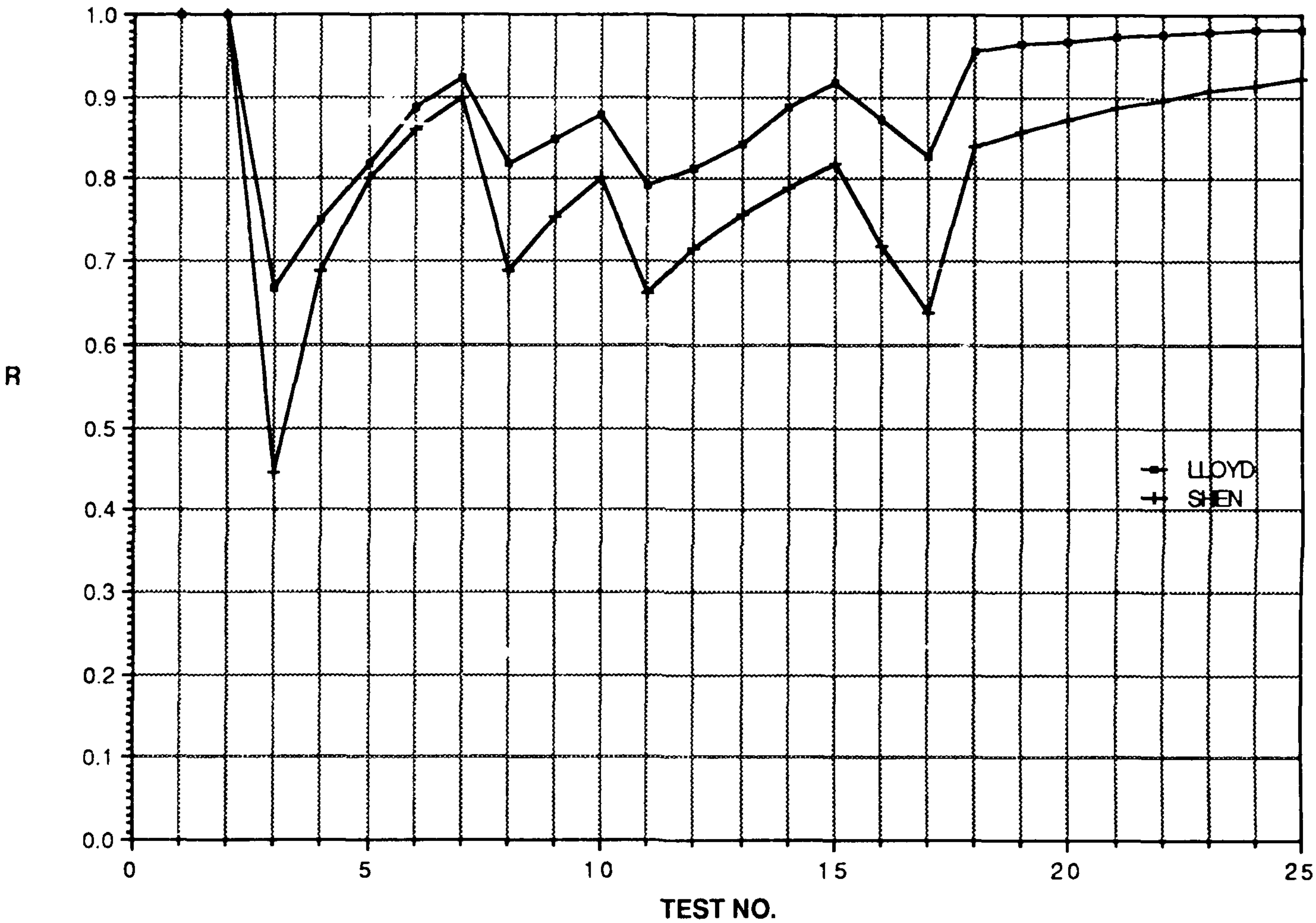


Figure 11. Lloyd vs. Shen comparison.

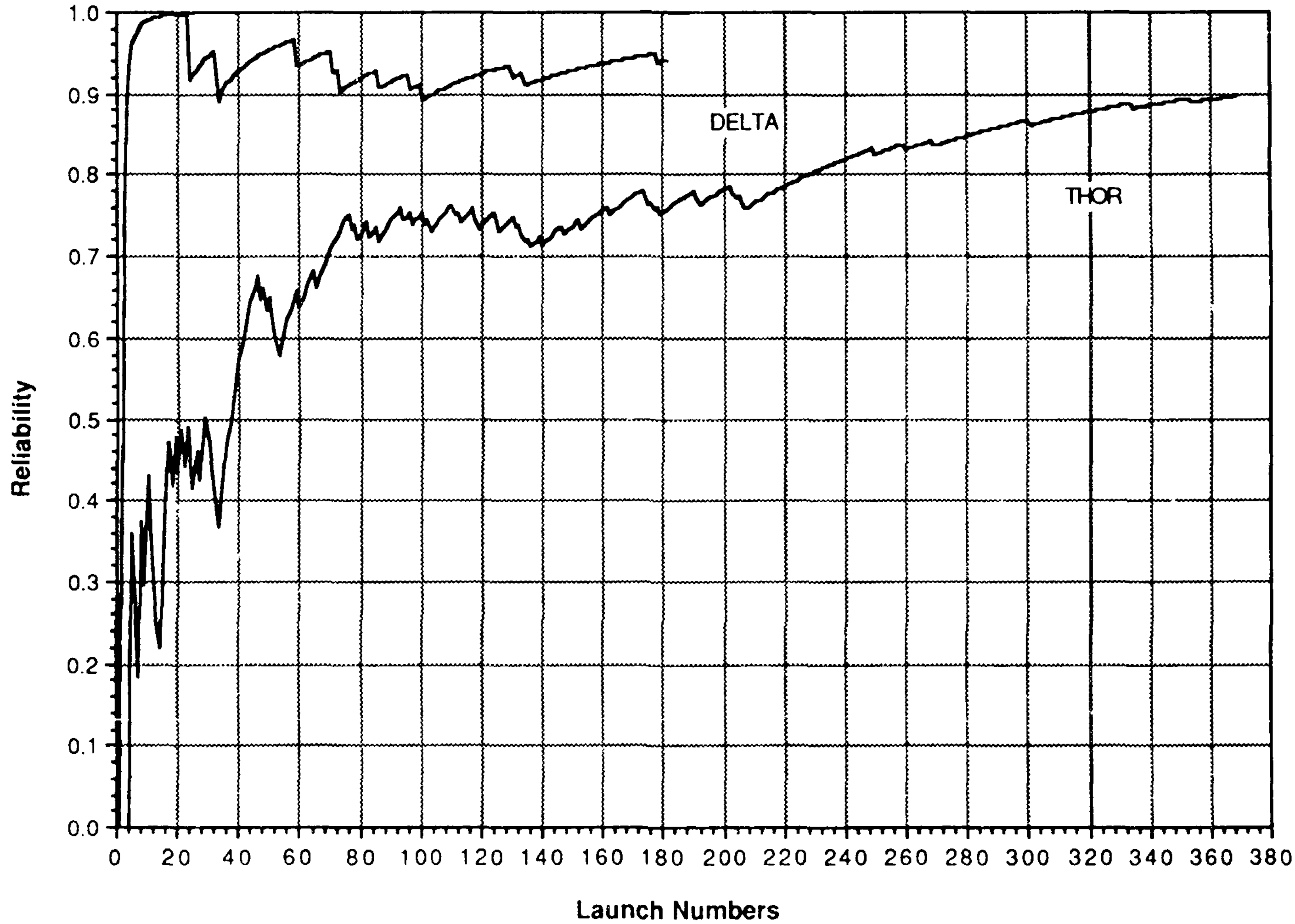



Figure 11a. Reliability estimation of Thor and Delta.

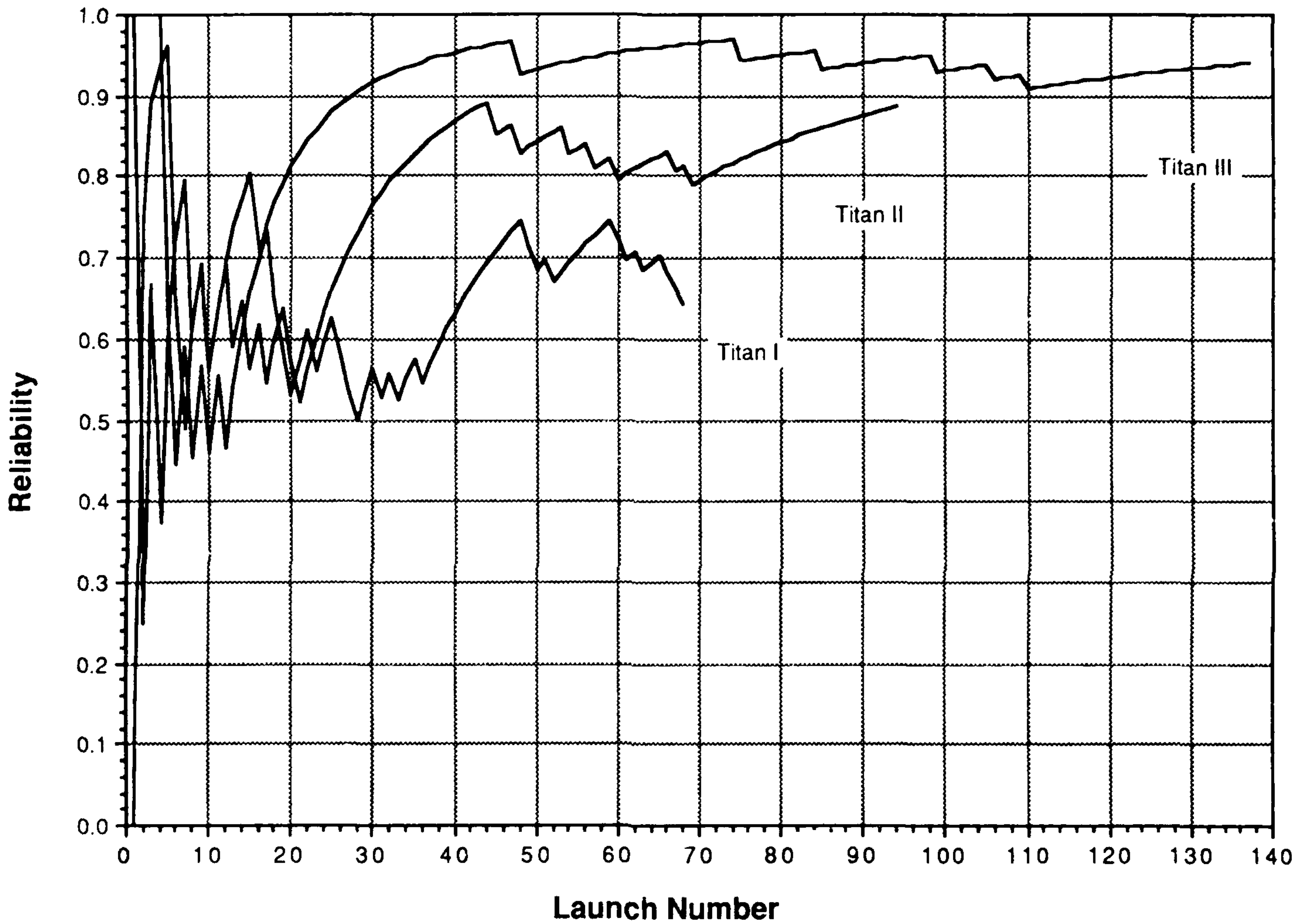



Figure 11b. Reliability estimation of Titan I, II, III.

### 3.1.2 PRACA/FRACA Trending

An additional dimension could be added to PRACA/FRACA system to allow trending if a "cradle to grave" concept were established. Under the current circumstances PRACA/FRACA systems frequently report only through the testing phase (except for reusable systems) and do not always report on total time and cycles on both failed and unfailed components.

In addition, PRACA/FRACA systems should include not only failure phenomenon but precursors to failure problems as well. Such precursor problems should include unexpectedly low margins or larger than expected variability. The corrective actions should be accomplished interactively with system functional descriptions and the FMECA to insure that those efforts are up to date while the search for root cause is pursued.

In order for an evaluation of PRACAs/FRACAs trending capabilities to be affected, a pilot program needs to be established using the trending techniques of reference 2.

### 3.1.3 Operating Characteristic Curves and Reliability

An example was given in Section 2.3.1.1 correlating operating characteristic curves to failure modes and failure rates. Reference 17 illustrates some recent work in this area. In this work an effort was made to tie safety factors developed in the traditional engineering approach to resulting structural reliability using a probabilistic representation of these traditionally developed factors.

Figure 12 illustrates the relationship of defect rates (quality of submitted lots) to operating characteristics (OC) curves. In this way, changes in sampling plans and procedures could be linked to criticality ranking in FMECAs.

For example, suppose the amount of moisture in a bonding liner polymer used in solid rocket motor cases is linked to poor quality of bonding, thus to separation. A change in the sampling procedure could reduce the defect rate and reduce the potential for failure by a similar amount.

A study should be undertaken to test the validity of such a link.

## 3 2 Evaluation of Qualitative Methods

As was noted earlier, it is difficult to prioritize qualitative methodologies. However, the three methods that do show promise based upon the information obtained from this study effort are:

- Top Down Analysis
- Product Design FMEAs
- Manufacturing Interfaces

Tests of these techniques could help to more firmly establish these capabilities. Suggested tests are defined below:

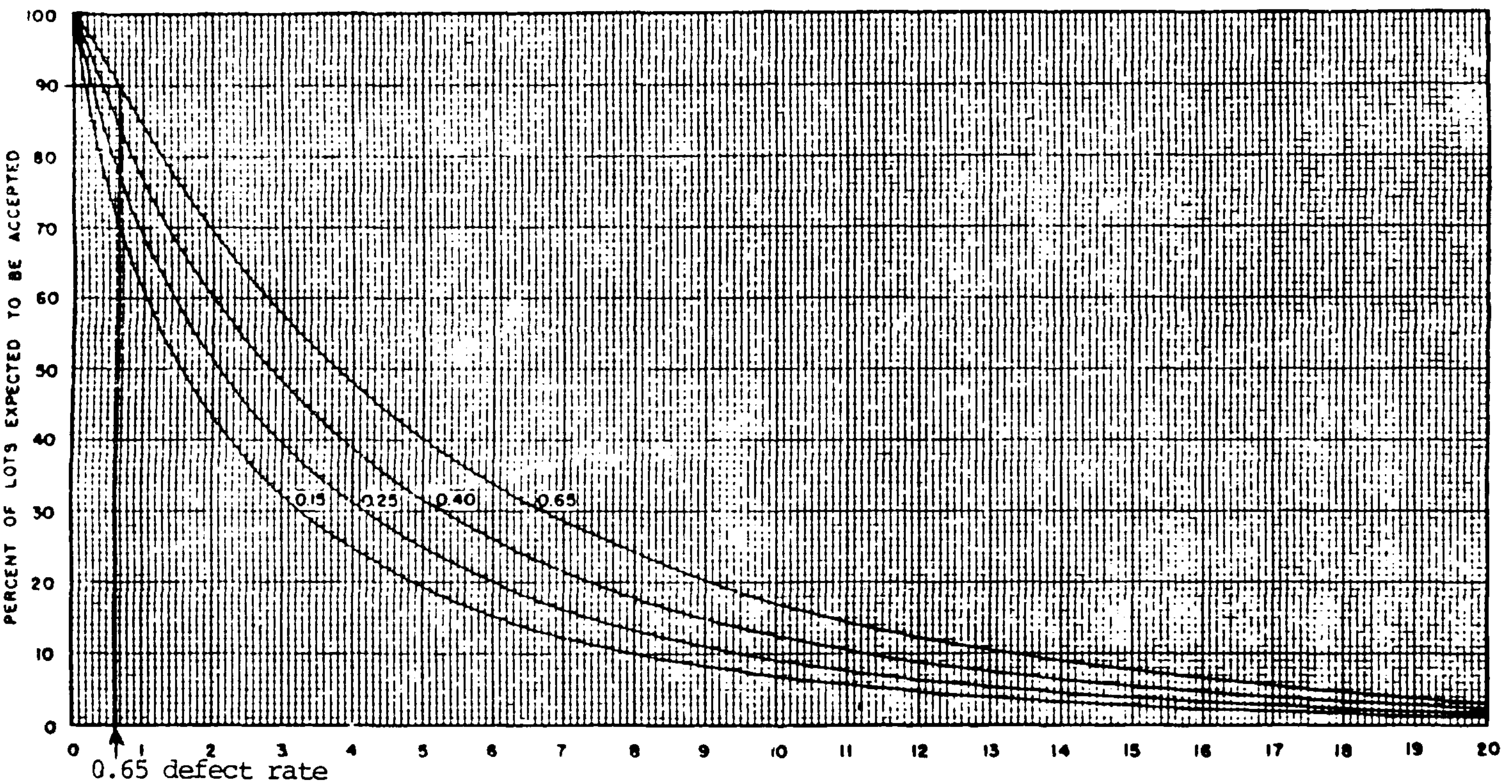
### 3.2.1 Top Down Analysis

In order to rate the value of "Top Down Analysis" when conducted in accordance with the method

SAMPLE SIZE CODE LETTER

F

( Curves for sampling plans based on range method and known variability are essentially equivalent )




The values of the percent of lots expected to be accepted are valid only when measurements are selected at random from a normal distribution.

Note: Figures on curves are Acceptable Quality Levels for normal inspection.

Figure 12. Operating characteristic curves for sampling plans based on standard deviation method.

described in Section 3.2.1.2, the results of an FMEA should be compared to the results of a Top Down analysis.

### 3.2.2 Product Design FMEAs

Product Design FMEAs have proved to be valuable in identifying and eliminating sources of common cause failures in electrical/electronics applications (see Section 2.3.1.2). A study should be undertaken to see if a Product Design FMEA would be fruitful when applied to the non-electronic propulsion subsystems.

### 3.2.3 Manufacturing Interfaces

Flight critical item and manufacturing control plans have a great deal of potential for controlling critical items as described in Section 2.3.1.2 "Manufacturing Control FMECAs". The effectiveness of such an approach remains to be demonstrated, however. A study should be undertaken to demonstrate the effectiveness of manufacturing control FMECAs.

## 3.3 Prioritization of Methodologies

The prioritization of methodologies cannot be completed until the studies described in this section are completed.

## KEY RECOMMENDATIONS

The following areas have been identified as having significant reliability impact. These areas each warrant further in-depth study if the high reliability goals of the Air Force advanced launch vehicle programs are to be achieved in an operational system.

### 1. Failure Correlation*

The percentage of failures which are likely to impact more than one engine in a multi-engine design is of critical design import. This percentage, or "failure correlation factor," must be well below 20% for reliability oriented design approaches such as engine out capability to be effective. The lower this percentage the more effective is this hueristically pleasing design option. Not surprisingly therefore, contractor new engine design characteristics quote extremely low factors (as low as 1%). Correlations as low as 1 out of 100 do not seem consistent with other design parameters specified (such as high chamber pressures) and are considerably lower than factors achieved on recent engine designs (e.g. 17% for the shuttle main engine test program). Finally, there did not appear to be any significant consideration given to how these low factors would be achieved in practice.

Recommendation 1 - Failure correlation factors are key reliability parameters to Air Force launch vehicle design decision makers. Specific studies such as parameter design studies which address what factors have been achieved in the past and what design trades have been made to ensure the low factors quoted will be evident in the resulting designs appear to be lacking. It is recommended that these investigations be made prior to the selection of any design alternative.

### 2. Variability Control

The currently achieved launch vehicle reliability has been shown by this investigation to be below 0.95. However, the investigation uncovered examples of reliabilities in other somewhat similar systems, such as tactical missile systems, which routinely achieve 0.99 and some which approach 0.999. These systems whose operational reliabilities currently meet or exceed the reliability requirements for the Air Force advanced launch system have achieved these high reliability levels through the use of intensive variability control programs. While it would be inappropriate to make any direct correlation between tactical missiles and launch vehicles, it is also clear from a review of the failure data of mature launch systems that the barrier to significantly higher reliabilities may be the residual variability inherent in the current launch vehicle production process. A cursory review of other somewhat comparable products, such as commercial jet engines and gas turbines and recent Air Force variability reduction studies performed as part of the R&M 2000 program, provide further support for this argument.

Recommendation 2 - Residual variability may be the key barrier to high launch vehicle reliability achievement. For this reason, it is recommended that investigations be made into the effectiveness of specific variability control programs such as Taguchi methods or alternatives. These investigations should be directed at determining the applicability of the methods to the launch vehicle production process. It is further recommended that some specific program for variability control be included throughout all phases of the advanced launch system program.

* The definition cited here is broader than that used traditionally by propulsion system designers. See Appendix A.1 for discussion of the difference.

3. Reusability

Reusability is, on the surface, a design goal of significant program benefit. However, the benefits of reusabiity are significantly compromised if the reliability of an engine is adversely affected by the requirement. Besides the direct costs involved in developing a reusable design, there also appears to be significant indirect costs which are required to maintain reliability in a reusable design. For example, reusability by its very nature tends to decrease the production run. When production runs are decreased, investments in automated production equipment become less economical and the production process therefore tends to become more prototypical. Prototypical production, especially of complex equipment, increases the problems associated with variability control and therefore substantial postproduction testing may be required to ensure high reliabilities. A good example of such an indirect impact on reusability was seen at the Rocketdyne SSME production facility in Canoga Park, California.

Recommendation 3 - Reusability has been shown to have indirect and potentially negative impacts on the achievement of high reliabilities at reasonable cost. The indirect impacts of reusability on reliability and cost through such mechanisms as variability control problems should be thoroughly investigated and the results of this investigation included in the programmatic decision making related to reusability.

4. Risk Management

Achievement of high operational reliabilities in such areas as nuclear power plant safety systems have been significantly supported by a continually active program that attempts to identify the risks to reliable operation and to address them according to their importance. Such a risk management program has been investigated and recommended by NASA SRM & QA for future projects, but it is not clear whether a risk management program is planned for the acquisition of advanced launch systems.

Recommendation 4 - The Air Force should investigate the advisability of incorporating a risk management program as an integral part of any launch system program.

5. Reliability Performance Indicators and Trending

For high reliability programs it is important to identify, early on, symptoms of the process which presage deterioration in performance. This has been done in the financial community, in the commercial aircraft community and in the nuclear power safety community by the development of a set of "leading" performance indicators and developing performance trends based upon the indicator trajectories through time. If such a set of indicators could be developed and trended for the Advanced Propulsion Systems program, the indicator trajectories might provide early warning of problems arising during development and operation. This early warning could provide the time required to institute corrective action before actual program reliability performance is affected.

Recommendation 5 - The Air Force should develop as part of advanced propulsion system development programs a set of potential indicators of programmatic reliability performance. This indicator set should be based originally on historical information, but later updated and validated as advanced propulsion system development programs specific information becomes available.

6. Reliability Growth Analysis

In all developmental systems a certain degree of reliability growth is to be expected. However, program managers need to know the pace of the expected growth so that they can determine if the program is likely to meet the operational reliability goals within developmental time constraints An understanding of the growth process is therefore essential to the determination of the proper role to be played by history in the forecasting of future system reliability. If an historical failure has been analyzed and its cause determined and suitable corrective action is implemented to prevent its recurrence, it is recognized that it would have its probability of occurring again diminished when it is utilized for predicting future performance. But by how much? The determination of how much each failure should be counted is important in order to establish the proper "calibration" for the reliability growth characteristic to be used to determine how well reliability development is proceeding. Several approaches have been developed to address the issue of growth. Among those developed are the early works of Duane at GE, that of David Lloyd of TRW, and that developed by Dr Yu Shen of SAIC as part of this study. In addition, Bayesian approaches may show promise for improved growth forecasting.

Recommendation 6 - Reliability growth forecasting is important during the development of systems with high reliability requirements such as ALS. Accurate growth forecasts allow program managers to determine early on if reliability requirements are likely to be met. (This is especially important when program economics prohibit extensive development test flights as is the case with ALS). Several methods currently exist to allow for forecasts to be generated; however, further development is required to assure that a reasonable growth forecast is developed for advanced propulsion system development programs. It is therefore recommended that the concept of reliability growth be further developed as it applies to advanced propulsion system development programs.

Further Recommended Studies - The recommended studies as discussed in Section 3.0 are judged to be somewhat less in importance than the Key Recommendations above. Nonetheless, the following recommended studies could have a significant impact on reliability.

1. Detailed Comparison of the Methods of Secion 2.2

2. PRACA/FRACA Trending

3. O.C. Curves and Reliability

4. Top Down Analysis

5. Product Design FMEAs

6. Manufacturing Interfaces

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# Appendix A.1

## An Investigation of Historical Failure Correlation Using the Shuttle SSME Test and Flight History as an Example

## INTRODUCTION

Given the current state of rocket engine technology there exists a finite probability of a catastrophic engine failure during a vehicle launch. A catastrophic engine failure is considered one in which the engine does not shut down in a controlled manner and includes uncontrolled fire, explosion, breach of the pressure boundary, shrapnel, or a combination of these. Given that an engine has failed catastrophically in flight an immediate concern is for other critical hardware in the vicinity of the failed engine. For vehicles configured with multiple engines in a cluster the question become whether the catastrophic failure of one engine will result in the catastrophic loss of the entire engine cluster.

This study develops the correlation between a catastrophic failure of a Space Shuttle Main Engine (SSME) and the propagation of that failure to include the entire SSME three engine cluster.+

## SSME FAILURE DATABASE

The SSME database used for this study consists of ground test and flight data from May 19, 1975 through April 20, 1988. The database includes 1450 records detailing the SSME exposure history by test and date.

Significant SSME events which have resulted in damage or the loss of hardware are classified by NASA as major incidents. Catastrophic engine events are a subset of the events classified as major incidents. A catastrophic event is one in which its occurrence in flight results in significant uncontained engine damage and subsequently in the loss of crew and vehicle. The consideration of major incidents is the basis for developing the correlation of failure factor for the SSME.

Within the total SSME experience there have been 36 major incidents. Of these 32 of these incidents have been during single engine ground tests, which must be judged as applicable to this study and whether the event would have resulted in damage to an engine cluster. Three of the major incidents occurred during three engine cluster static firings and it should be noted that none of these events resulted in damage to the other engines in the cluster. The remaining major incident occurred in flight during the STS-11 mission and again did not result in damage to the cluster, however, this event occurred late in the engine burn with no consequence to the engine involved and the engine shut down at its programmed time.

The failure events included in the study consider all SSME history and has not been filtered. Since the major consideration is to determine the probability of cluster failure given an engine failure has occurred, all of the SSME experience is considered. Thus, engine configuration, test objectives, power level, subsequent hardware redesigns, etc., are considered irrelevant. The object of this study is not to determine whether the SSME will fail, but, given that one has failed, to determine the probability of an entire cluster failure.

Failure Criteria - Not all of the 36 major incidents are applicable to this study. Since the study involves failures which could potentially affect or damage other engines of the cluster an appropriate screening criteria is required in order to determine which of the major incidents in the database are applicable. The criteria used to develop the correlation of failures must consider only those events which either directly damage the cluster due to shrapnel, for example, or which indirectly result in cluster failure by disrupting the fuel flow to all engines.

+ During the course of this study a descrepancy in the definition of "correlation factor" was discovered between the propulsion system developers and the ultimate launch vehicle users (here the US Air Force). The propulsion system developers limit correlated failures only to catastrophic engine failures which would propagate to a cluster as is discussed in this section. To the user any failure which causes loss of more than a single engine whether via catastrophic failure, unscheduled shut down, loss of fuel supply, improper thrust vectoring, etc. so that the payload to orbit capability is jeoparadized is a correlated failure. In this way, catastrophic engine failures which propagate are only a subset, albeit an important one, of all correlated failures.

The following criteria were used to determine which of the major incidents should be considered applicable for this study:

Uncontrolled SSME Shutdown - The event occurred in such a way that the SSME controller was not in control of the shutdown sequence. That is, the failure mode is one which can not be or is not redline protected; or even though redline protection exists and may have been activated, the action of the controller is insufficient or is not fast enough to maintain control of the event.

Uncontained Hardware Failure - The failure of an engine component results in uncontained damage or damage propagation to other major components such as in the case of an uncontrolled oxygen fire or in the event of an explosion in which debris and shrapnel cause subsequent hardware failures. Of primary concern to the surrounding engines of the cluster is breach of the engine pressure boundary and the release of hot gas, fire or shrapnel.

Retirement of an Engine from Further Testing - Due to the limitations in some of the failure descriptions additional data is required to make a judgement as to the applicability of an event. One readily available piece of information is the subsequent disposition of an engine following an event. Retirement of an engine from the test program is generally a good indication that the damage to the engine resulting from the incident was severe enough to preclude use of the hardware in the future. It is recognized, however, that this is not a definitive indicator of severe engine damage since engines are retired as a function of their firing exposure as well as according to damage resulting from testing.

The above criteria are thus used to determine if a major incident should be considered an applicable failure to consider in developing the correlation of failure factor. Once the event is judged applicable a final criteria is used to determine if there is the potential for damage to the engine cluster.

Damage to Surrounding Hardware - Only in the flight configuration and in the three engine cluster static firing is direct indication of damage to an adjacent engine available. Thus, for single engine test firings an indirect indication of propagation of the failure to adjacent engines is damage to surrounding hardware, particularly the test stand itself. The extent of damage to the test stand is generally available and provides a good indication of the severity of the failure.

Due to the limited data available at the time of this study, for incidents in which the available failure description is not sufficient to determine the extent of damage to the surrounding hardware one available piece of data is the test stand down time following an event. Note that a long down time following an event is not necessarily an indication of damage to the test stand, but may indicate a lack of available test hardware, schedule considerations, ongoing failure investigation, or the installation of the next test engine. However, a short down time following an event is a definite indication of little or no damage to the test stand.

If essentially no damage to surrounding hardware resulted from the incident then propagation to the cluster is not considered likely. If damage was done to the surrounding hardware or the test stand the severity of the event is considered and a judgement is made as to whether the event would propagate to the cluster. Events in which the effect on adjacent engines is not clear are ranked as not propagating to the cluster.

Application of this criteria thus provides a framework within which to judge the 36 major incidents as to whether they are applicable to this study. Given that a failure is considered applicable for final consideration, and based on the severity of the post event damage, it is ranked as to whether the event would propagate to a cluster failure.

## SSME FAILURE SUMMARY

There are a total of 36 major incidents in the SSME database which were evaluated for the purposes of this study. Of these, 18 are considered to be applicable to this study in that they meet the criteria described previously. They are indicated in the failure summaries by an asterik (*) following the test number. Of these 3 major incidents are considered failures which would have propagated to adjacent hardware and would result in failure of the entire cluster. These are indicated by an additional asterik (**).

Table 1 summarizes all 36 of the major incidents considered in this study. In addition to providing information about the event, such as test number, test date, engine number, configuration, the table details the results of implementing the criteria evaluation.

## SSME MAJOR INCIDENT DESCRIPTIONS

The SSME major incidents are discussed chronologically in the following paragraphs. The event is described and the rationale for its use in developing the correlation of failure factor is discussed.

Test 901-110* - During test 901-110 (UCR A005353) rubbing in the HPOTP of engine 0003 caused failure of the primary lox seal and an uncontained engine fire. The redline cut was set by a HPOTP overspeed. This failure resulted in an increase of the intermediate seal purge pressure, revised redlines, and a design change from a lift-off seal to a labyrinth seal design.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-133 - Test 901-133 (UCR A005072) experienced a burn-through of the FPB wall during testing of engine 0004. The test was cut by an observer. This failure resulted in uncontrolled engine shutdown and damage to the engine. The engine survived this event and was used for later testing. Since the engine was not severely damaged and there is no indication of test stand damage (operational again in 6 days) this failure is not considered applicable to the study.

Test 901-136* - A failure of engine 0004 HPOTP turbine end bearings occurred during test 901-136 (UCR A005350) which resulted in an uncontained engine fire. The test was cut by an observer. The failure resulted in design changes to heavy duty 209 series bearings, improved bearing mounts and modifications to the coolant circuit orifice.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 902-095 - During test 902-095 of engine 0002 (UCR A008624) a leading edge airfoil crack resulted in blade failure, however, the engine damage was contained. The redline for the test cut was from the HPOTP radial accelerometer. Design and process changes have been implemented to increase blade life.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand (operational within 11 days) in the available documentation. This failure is not considered applicable to this study.

Test 901-147* - HPFTP turbine blade failure of engine 0103 during test 901-147 (UCR A005094) resulted in a rapid power loss, reduced fuel flow and LOX rich operation of the engine. The test was cut by the HPOTP radial accelerometer redline. As a result, HPFTP turbine blade and damper redesigns were initiated.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand (operational within 11 days) in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-173* - Main injector lox post failure, cut off by HPFTP turbine discharge temperature.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-183 - Main injector lox post failure occurred during test 901-183 (UCR A018710) of engine 0002. Cutoff was by the HPFTP turbine radial accelerometer. The failure resulted in the incorporation of lox post flow shields.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand in the available documentation. This failure is not considered applicable to this study.

Test 902-112 - During test 902-112 (UCR A019208) of engine 0101 on June 10, 1978 a blockage of the fuel supply resulted in a HPFTP turbine overspeed. The redline cut for the test was the HPFTP turbine speed.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand in the available documentation. This failure is not considered applicable to this study.

Test 902-120 * - During test 902-120 (UCR A005745) of engine 0101 structural failure and rubbing of a capacitor position instrumentation sensor in the HPOTP resulting in engine fire and uncontained engine damage. The test was cut by the PBP axial accelerometer redline. The capacitance device is no longer used.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although the capacitance device is no longer used it does demonstrate the result of a HPOTP failure, subsequent fire and shrapnel. This failure is considered applicable to the study and although some damage was noted to the test stand it would not have propagated to a cluster failure.

Test 902-132 - During test 902-132 (UCR A005780) of engine 0006 a f [illegible] occurred as the result of the MOV being clocked wrong. The test was cut by the low chamber pr[illegible] redline. The failure resulted in a guideline for the first test of a new engine to be only 1.5 seconds.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand in the available documentation. This failure is not considered applicable to this study.

Test 901-222 - During test 901-222 (UCR A017972) of engine 0007 a failure occurred as a result of undetected internal HEX damage caused during arc welding which resulted in an engine fire. HEX coil leakage resulted in an uncontained engine fire and severe damage. The test was cut by the HEX discharge pressure redline. The leak was caused by wall thinning of the HEX coil which occurred during welding and reaming operations. The failure resulted in increased HEX proof test requirements.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 901-225* - During test 901-225 (UCR A01816) of engine 2001 flow induced fretting of the MOV sleeve resulted in autoignition, fire and explosion. The test was cut by the HPFTP turbine discharge temperature redline. The incident resulted in several design modifications (ECP's 248, 258, 271) including a redesigned MOV inlet sleeve/seal area and the incorporation of a vibration redline.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-041* - During testing of engine 0201 on May 14, 1978, the steerhorn tube fractured due to high structural loading (UCR A006466). The test was cut by the HPFTP turbine discharge temperature redline. The failure resulted from structural fatigue associated with high strain accelerations attributed to exhaust gas flow shock phenomena during start and cutoff transients causing failure of the flight nozzle steerhorn fuel distribution manifold. The failure resulted in fuel starvation and loss of mixture ratio control. Engine damage as a result of the high temperature was extensive and included the HPFTP, HPOTP, nozzle, main injector and the high pressure fuel distribution manifold steerhorn damage. The failure resulted in redesign of the feedline assembly and nickel plating of steerhorn tees.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Static Firing 6-01 - During Static Firing 6-01 (UCR A009437) high cycle fatigue resulted in the failure of engine 2002 MFV housing, fuel leakage and fire. The test was cut by the HPFTP turbine discharge temperature redline. The MFV housing crack extended from the cap flange to the outlet flange. The failure resulted in housing design modifications (ECR 09738). Rework housing cam bearing cutout to reduce stress concentration.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine during a three engine cluster firing. The failure resulted in fuel leakage and fire during the ground test. In flight, the chance of fire is a function of the available oxygen which is altitude dependent. There is no indication of significant damage to the other engines or to the test stand. The engine survived this event and was used for later testing. Damage to the engine was not significant and this event is not considered applicable to the study.

Static Firing 6-03* - Testing of engine 0006 (engine position 3) during a cluster firing on November 4, 1979, resulted in a nozzle steerhorn rupture (UCR A010997). The test was cut by the HPOTP intermediate seal purge pressure redline. The failure was traced to use of an incorrect weld filler wire during fabrication. The failure resulted in the implementation of stringent weld wire audits. Added nickel plating to tee weld joints and redesigned to incorporate steam loop.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine during a three engine cluster firing. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the adjacent engines or to the test stand in the available documentation this failure did not propagate to an engine cluster failure.

Test 902-198* - Main injector lox post failure resulted during test 902-198 of engine 2004. Cutoff was by the HPOTP turbine discharge temperature redline. The failure resulted in a change from the existing injectors to Haynes 188 lox post tips in rows 10 through 13. New injectors have all Haynes 188 lox posts.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-284* - During test 901-284 (UCR A015786) of engine 0010 a malfunctioning MCC chamber pressure lee jet caused the controller to lower the HPOTP output and resulted in HPOTP fire and external damage. The test was cut by HPOTP accelerometer redlines. The failure resulted in installation of a positive retainer in Pc port flange to prevent lee jet from backing out.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although redesigns have been implemented this failure does demonstrate the result of a HPOTP failure, subsequent fire and shrapnel. This failure is considered applicable to the study and although some damage to the test stand was noted, it would not have propagated to a cluster failure.

Static Firing 10-01 - During Static Firing 10-01 (UCR A015391) of engine 0006 a burn-through of the FPB liner and housing occurred. The test was cut by an observer. The failure resulted in the addition of a molybdenum insulator and new divergent ring liner.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine during a three engine cluster firing. The failure resulted in external leakage of hot gas from the FPB burn through. There is no indication of significant damage to the other engines or to the test stand. The engine survived this event and was used for later testing. Damage to the engine was not significant and this event is not considered applicable to the study.

Test 901-307* - During test 901-307 of engine 0009 a failure occurred in which the FPB injector experienced a burn-through. This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-140 - Main injector lox post failure resulted during test 750-140 of engine 0110. This failure resulted in a controlled engine shutdown and contained engine damage. The engine survived this event and was used for later testing. Thus, this failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 901-331* - During testing of engine 2108 on July 15, 1981, injector post and engine damage was caused by material failure of the lox posts (UCR A013786). The test was cut by the HPOTP turbine discharge temperature redline. The failure resulted in the application of new materials for the lox posts and the addition of flow shields.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-148 - Main injector lox post failure resulted during test 750-148 (UCR A016031) of engine 0110. Cutoff was by the HPOTP turbine discharge temperature redline. The failure resulted in the implementation of all Haynes 188 lox posts and extended flow shields.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 902-249* - The HPFTP inlet volute of engine 0204 failed during test 902-249 (UCR A018288) as a result of non-standard fuel preburner injector modifications which produced a hot FPB core. A group of plugged FPB LOX posts created a hot spot and delamination of the Ni/Rene first stage blade tip seal, resulting in blade failure, shrapnel and inlet volute rupture. The test was cut by the HPFTP radial accelerometer redline. The resulting fire destroyed both turbines, the powerhead, MCC and nozzle. This failure resulted in a design change to all Rene blade tip seals and preburner modification restrictions to preclude a "hot core."

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although fixes have been implemented this failure does demonstrate the result of turbine blade failure and subsequent fire and shrapnel. This failure is considered applicable to the study and although some damage to the test stand was noted, it would not have propagated to a cluster failure.

Test 901-340 - A HPFTP turbine discharge sheet metal failure of weld 56 during test 901-340 (UCR A018305) of engine 0107 caused turbine flow blockage and resulted in contained turbopump damage. The test was cut by exceeding the HPFTP turbine discharge temperature redline. The failure resulted in weld prep redesign to achieve 100% penetration and the inclusion of x-ray inspection where accessible.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 750-160* - A blockage of the fuel supply as a result of ice formation occurred during test 750-160 (UCR A016045) of engine 0110 which burned both turbines, HGM, main injector, MCC and nozzle. The test was cut by the HPFTP turbine discharge temperature redline. The failure resulted in revised engine drying procedures to remove all water following EDM operations.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-364** - A new redesigned Kaiser cap nut allowed hot gas leakage into the coolant circuit during test 901-364 (UCR A006810) of engine 2013 which resulted in bearing failure, uncontained engine damage and complete destruction of the engine. The failure produced significant shrapnel and test stand damage with the engine ultimately separating from the test stand. A redline cut was set by the PBP radial accelerometer. The redesigned nut was tested no further and all engines continue to use the original design.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although this hardware configuration is no longer in use it does demonstrate the result of a loss or disruption of coolant flow to the turbomachinery. This failure is considered applicable to the study and would have propagated to a cluster failure.

Test 750-165 - During test 750-165 of engine 0107 the OPOV experienced seal erosion. The test continued for the programmed duration. This failure resulted in a controlled engine shutdown and contained engine damage. The engine survived this event and was used for later testing. Thus, this failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 750-168 - During test 750-168 of engine 0107 ASI blowback caused post cut-off OPOV ball seal leakage. Inspection revealed the seal was cracked and eroded. The test continued through the programmed duration. The shutdown sequence and purge requirements were revised.

This failure resulted in a controlled engine shutdown and contained engine damage. The engine was retired following this event. Thus, the failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 750-175** - The HPO duct of engine 2208 was modified with the installation of an ultrasonic flow meter. During test 750-175 (UCR A011506) a failure resulted in HPOTP overspeed to 44,000 rpm (nominal 27,300 rpm) causing disc rupture, pump fire, shrapnel and extensive engine damage. The test was cut by the PBP accelerometer redline. The failure occurred at the brazed joint between the prototype ultrasonic flowmeter and the high pressure oxidizer turbopump discharge duct and resulted in destruction of the HPO duct, the HPOTP, the HGM and the controller. Further use of ultrasonic flow meter on HPO duct was eliminated.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although this hardware configuration is no longer in use it does demonstrate the result of a loss of oxidizer flow and subsequent HPOTP turbine overspeed, lox fire and shrapnel. This failure is considered applicable to the study and would have propagated to a cluster failure.

STS-11 - One major incident actually occurred in flight during STS-11 and was obviously not catastrophic. During the flight the ASI chamber of engine 2015 experienced erosion due to a drill chip lodged in an ASI orifice. Engine cut-off was by programmed duration The failure resulted in the addition of an ASI fuel filter to the supply line.

The engine burn continued for the programmed duration. This failure resulted in a controlled engine shutdown and contained engine damage. Although there was damage to the engine itself, there was no damage to the adjacent engines. The engine survived this event and was used for later testing. Thus, this failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 901-436* - A hydrogen leak during test 901-436 (UCR A013338) of engine 0108 overpressurized the HPFTP coolant cavity and resulted in a coolant liner failure and major engine damage, destroying both turbines, the powerhead, MCC and nozzle. A redline cut was issued due to high HPFTP turbine discharge temperature. Design changes were incorporated to decrease hot gas leakage into the coolant circuit, a coolant liner pressure redline was implemented and inspection requirements were increased on the coolant liner close-out weld.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-468 - During test 901-468 (UCR A014585) of engine 0207 a stress concentration at the welded boss caused the FPB manifold to crack resulting in fire and major engine damage. This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-259** - A failure of the MCC outlet manifold weld occurred during test 750-259 (UCR A015713) of engine 2308 and resulted in complete engine destruction. The failure resulted in shrapnel and test stand damage with the engine ultimately separating from the test stand. The test was cut by the HPFTP accelerometer and turbine discharge temperature redlines. Failure investigation determined that the MCC outlet assembly had ruptured due to fatigue or undetected flaws. The failure resulted in improved inspection of the assembly, redesign of the outlet neck and splitter and implementation of life limitations on other MCC's.

This failure resulted in uncontrolled engine shutdown, destruction of the engine and significant damage to the test stand. This failure is considered applicable to the study and would have propagated to an engine cluster failure.

Test 750-285 - A Class I leak was experienced during test 750-285 at the number 8 feedline. Engine 0210 (May 21, 1987) experienced a feedline crack at the saddle bracket stop weld. The test was cut by a facility ambient air thermocouple. The failure resulted in improved feedline/saddle bracket and weld interference inspections.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 902-427 - During testing of engine 2106 on June 26, 1987 at the NSTL A-2 test stand the low

pressure fuel pump discharge duct experienced a corrosion induced leak and subsequent external hydrogen fire. The test was cut by an ambient powerhead temperature redline. To preclude the possibility of corrosion induced failures, flight engines will use low pressure fuel turbopump discharge ducts with low calendar life and/or hotfire time (DAR 2074). Subsequent flight engines will use corrosion protected low pressure fuel turbopump discharge ducts (ECP 977).

This failure resulted in uncontrolled engine shutdown , however the damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 902-428 - During test 902-428 of engine 2106 a crack in the OPB interpropellant plate resulted in the formation and build up of ice, blocking the fuel supply which altered the OPB exhaust flow distribution and burned through the liner causing faceplate erosion and HPOTP turbine end damage. The test was cut by a facility redline. The failure was caused by cracks in the interpropellant plate-to-element braze joints. The cracks allowed propellant mixing and caused ice contamination to form in fuel manifold. The failure was determined to be the result of poor braze joints made during fabrication. Flight engines are cleared by a review of the manufacturing braze joint records.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

## ANALYSIS

The results of applying the criteria to the SSME major incidents database results in a total of 18 applicable failures, of which 3 are considered to propagate to a cluster failure.

The mean is then computed by

$$\bar{X} = 3/18 = 0.167$$

Due to the small sample size the $F$ distribution is assumed in order to develop the confidence interval for this case. For a 95% confidence interval the results of applying the $F$ distribution are

$$0.036 < \bar{X} \leq 0.414$$

Thus, with a 95% confidence interval the probability that a failure will propagate to the adjacent engines in the cluster is between 4% and 41%, given that an uncontrolled engine failure occurs.

## CONCLUSIONS

In the development of future launch vehicles the potential benefit of engine out capabilities must be weighed against the risks that if an engine fails in an uncontrolled manner it will result in the loss of the entire engine cluster. This study evaluated the SSME which is flown in a three engine cluster. No uncontrolled SSME failures have occurred in flight. Only a limited amount of ground testing has actually been done in a three engine cluster and although failures have occurred none have propagated to involve the entire cluster.

However, the test data evaluated here indicates there is a reasonable probability, approximately 17%, that an uncontrolled SSME failure will propagate to the adjacent engines given that an uncontrolled failure occurs. The confidence interval is between 4% and 41% that a failure will propagate to the cluster with a 95% confidence level.

TABLE A.1: SSME CORRELATION OF FAILURE FACTOR

| 32 TEST NUMBER | DATE | ENG | CONFIG | UCR | UNCNTD SHTDN | UNCONT HDWR FAILR | ENGN RETRD | APPLICBL FAILURE | SURRDG HARDWR DAMAGE * | CLUSTR DAMAGE ** | STAND DOWN TIME | R/L | COMP | COMMENT | TEST DURATN | C/O PWR LVL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 901.110 | 24-Mar-77 | 0003 | PRE-FMOF | A005353 | YES | YES | YES | YES | NO | NO | 52 | HO SPD | HPOTP | HPOTP FIRE EXT DAM | 74.07 | 75 |
| 901.133 | 27-Aug-77 | 0004 | PRE-FMOF | A005072 | YES | YES | NO | NO | - | - | 6 | OBS | FPB | HOLE IN FPB BODY | 48.21 | 90 |
| 901.136 | 8-Sep-77 | 0004 | PRE-FMOF | A005350 | YES | YES | YES | YES | NO | NO | 53 | CONT | HPOTP | HPOTP BNG FAILURE - EXT DAM | 300.22 | 90 |
| 902.095 | 17-Nov-77 | 0002 | PRE-FMOF | A008624 | YES | NO | NO | NO | - | - | 11 | HOACC C | HPFTP | HPFT TURBINE BLADE FAILURE-CROSSFEED | 51.09 | 70 |
| 901.147 | 1-Dec-77 | 0103 | PRE-FMOF | A005094 | YES | YES | YES | YES | NO | NO | 11 | HOACC C | HPFTP | HPFTURB BL FAILURE | 31.36 | 81 |
| 901.173 | 31-Mar-78 | 0002 | PRE-FMOF | A018710 | YES | YES | YES | YES | NO | NO | 34 | F TD T | MINJ | MINJ BURN THRO/REPLACED ENG | 201.17 | 92 |
| 901.183 | 5-Jun-78 | 0005 | PRE-FMOF | A019050 | YES | YES | NO | NO | - | - | 39 | HF ACC | MINJ | MINJ BURN THRO/REPLACE P/H | 51.10 | 100 |
| 902.112 | 10-Jun-78 | 0101 | PRE-FMOF | A019208 | YES | YES | NO | NO | - | - | 12 | HF SDP | FAC | HPFTP CAVITION/LN2 ON FAC SCREEN | 5.74 | 92 |
| 902.120 | 18-Jul-78 | 0101 | PRE-FMOF | A005745 | YES | YES | YES | YES | YES | NO | 35 | HOACC A | HPOTP | SPEC CAP INSTR/FIRE/EXT DAM | 41.80 | 100 |
| 902.132 | 3-Oct-78 | 0006 | PRE-FMOF | A005780 | YES | NO | NO | NO | - | - | 17 | PC IC L | MOV | MOV OFF POS AT PLATEAU/EXT DAM | 2.35 | 20 |
| 901.222 | 6-Dec-78 | 0007 | PRE-FMOF | A017972 | YES | YES | NO | NO | - | - | 14 | HEX PR | HEX | HEX FAIFURE/PROOF & LK CKS | 4.35 | 90 |
| 901.225 | 27-Dec-78 | 2001 | PRE-FMOF | A010816 | YES | YES | YES | YES | NO | NO | 40 | F TD T | MOV | MOV FRETTING-FIRE-EXT DAM | 255.63 | 100 |
| 750.041 | 14-May-79 | 0201 | PRE-FMOF | A006466 | YES | YES | YES | YES | NO | NO | 52 | F TD T | NOZZLE | NOZZLE STEERHORN FAILED | 4.32 | 100 |
| SF0601 | 2-Jul-79 | 2002 | PRE-FMOF | A009437 | YES | YES | NO | NO | - | - | - | F TD T | MFV | MFV BODY FAILURE | 18.49 | 100 |
| SF0603 | 4-Nov-79 | 0006 | PRE-FMOF | A010997 | YES | YES | YES | YES | NO | NO | - | SATS | CLUSTR | AFTER S/D STEERHORN RUPTURE | 9.72 | 100 |
| 902.198 | 23-Jul-80 | 2004 | FMOF | A017566 | YES | YES | YES | YES | NO | NO | 47 | O TD T | MINJ | HOLE IN INJ/LOX POST FAIL | 8.49 | 102 |
| 901.284 | 30-Jul-80 | 0010 | FMOF | A015786 | YES | YES | YES | YES | YES | NO | 28 | HOACC | MCC | LEE JET DISPLACED/EXT DAM | 9.89 | 60 |
| SF1001 | 12-Aug-80 | 0006 | FMOF | A015391 | YES | YES | NO | NO | - | - | - | OBS | FPB | HOLE BURNED IN FPB | 106.50 | 102 |
| 901.307 | 28-Jan-81 | 9 | FMOF | | YES | YES | YES | YES | NO | NO | 28 | | FPB | FPB INJECTOR BURNTHROUGH | 75.02 | 65 |
| 750.140 | 20-Jun-81 | 0110 | FMOF | | NO | NO | NO | NO | - | - | 7 | | MINJ | MAIN INJECTOR BURNTHOUGH | 300.00 | 109 |
| 901.331 | 15-Jul-81 | 2108 | PHASE I | A013786 | YES | YES | YES | YES | NO | NO | 24 | O TD T | MINJ | MINJ BURN OUT EXT DAM | 233.14 | 100 |
| 750.148 | 2-Sep-81 | 0110 | PHASE I | A016031 | YES | YES | NO | NO | - | - | 66 | O TD T | MINJ | MINJ BURN OUT/REPLACED MINJ | 16.04 | 105 |
| 902.249 | 21-Sep-81 | 0204 | PHASE I | A018288 | YES | YES | YES | YES | YES | NO | 75 | HF ACC | HPFTP | TURB BL FAIL/VOLUTE RUPTURE/EXT DAM | 450.57 | 109 |
| 901.340 | 15-Oct-81 | 107 | PHASE I | A018305 | YES | YES | NO | NO | - | - | 15 | F TD T | HPFTP | HPFTP T/A DUCT S/M BULGED | 405.50 | 109 |
| 750.160 | 12-Feb-82 | 0110 | PHASE I | A016045 | YES | YES | YES | YES | NO | NO | 33 | F TD T | ICE | H2O FROM EDM/EXT DAMAGE (CG1B) | 3.61 | 20 |
| 901.364 | 8-Apr-82 | 2013 | PHASE I | A005547 | YES | YES | YES | YES | YES | YES | 38 | HOACC C | HPFTP | KAISER HAT /TURB BNG EXT DAM | 392.15 | 109 |
| 750.165 | 21-Apr-82 | 107 | PHASE I | | NO | NO | NO | NO | - | - | 8 | | OPOV | OPOV SEAL EROSION | 280.00 | |
| 750.168 | 15 May-82 | 107 | PHASE I | | NO | NO | YES | NO | - | - | 42 | | OPOV | OPOV SEAL CRACKED AND ERODED | 300.00 | |
| 750.175 | 27-Aug-82 | 2208 | PHASE I | A011506 | YES | YES | YES | YES | YES | YES | 63 | HOACC | DUCT | HPO DUCT RUPTURE - EXT DAM | 115.64 | 111 |
| STS-11 | 3-Feb-84 | 2015 | PHASE I | | NO | NO | NO | NO | - | - | - | | OPB | OPB ASI CHAMBER EROSION | 527.89 | 65 |
| 901.436 | 14-Feb-84 | 0108 | PHASE II | A013338 | YES | YES | YES | YES | NO | NO | 36 | F TD T | HPFTP | CLNT LNR PR-MAJOR DAMAGE | 611.00 | 109 |
| 901.468 | 4-Feb-85 | 0207 | PHASE II | A014585 | YES | NO | NO | NO | - | - | 19 | PH/T | FPB | CRACK AT F-13 FLANGE-eng retired | 203.86 | 109 |
| 750.259 | 27-Mar-85 | 2308 | PHASE II | A015713 | YES | YES | YES | YES | YES | YES | 160 | HF ACC | MCC | DISCH MAN RUPTURE - EXT DAM | 101.47 | 109 |
| 750.285 | 21-May-87 | 210 | PHASE II | | YES | YES | NO | NO | - | - | 26 | | NOZZLE | CLASS I NOZZLE LEAK | 223.56 | 109 |
| 902.427 | 26-Jun-87 | 2106 | PHASE II | | YES | NO | NO | NO | - | - | 5 | | DUCT | LPFTP TURBINE DISCHARGE DUCT FAIL/FIRE | 138.36 | 104 |
| 902.428 | 1-Jul-87 | 2106 | PHASE II | | YES | YES | NO | NO | - | - | 41 | | OPB | OPB INTERPROPELLANT PLATE CRACK | 204.12 | 104 |

NOTES:

- ENG - ENGINE NUMBER
- CONFIG - ENGINE CONFIGURATION
- UCR - UNACCEPTABLE CONDITION REPORT
- UNCNTD SHTDN - UNCONTROLLED ENGINE SHUTDOWN
- UNCONT HDWR FAILR - UNCONTAINED HARDWARE FAILURE
- ENGN RETRD - ENGINE RETIRED FOLLOWING THIS EVENT
- APPLICBL FAILURE - FAILURE IS APPLICABLE TO THIS STUDY
- SURRDG HARDWR DAMAGE - EVENT RESULTED IN DAMAGE TO SURROUNDING HARDWARE
- CLUSTR DAMAGE - FAILURE WOULD RESULT IN DAMAGE TO THE ENGINE CLUSTER
- STAND DOWN TIME - DAYS FROM THIS EVENT UNTIL THE NEXT TEST ON THIS STAND
- R/L - REDLINE ISSUED FOR CUTOFF
- COMP - MAJOR COMPONENT INVOLVED IN EVENT
- C/O PWR LVL - CUTOFF POWER LEVEL

# SSME CHRONOLOGICAL EXPERIENCE

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901001 | 19-May-75 | 0001 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | | | |
| 901002 | 22-May-75 | 0001 | 1.00 | 1 | 0.00 | 0.00 | 0.00 | | | |
| 901003 | 2-Jun-75 | 0001 | 1.50 | 3 | 0.00 | 0.00 | 0.00 | | | |
| 901004 | 6-Jun-75 | 0001 | 0.80 | 3 | 0.00 | 0.00 | 0.00 | | | |
| 901005 | 12-Jun-75 | 0001 | 0.80 | 4 | 0.00 | 0.00 | 0.00 | | | |
| 901006 | 14-Jun-75 | 0001 | 1.00 | 5 | 0.00 | 0.00 | 0.00 | | | |
| 901007 | 23-Jun-75 | 0001 | 1.00 | 6 | 0.00 | 0.00 | 0.00 | | | |
| 901008 | 30-Jun-75 | 0001 | 0.50 | 7 | 0.00 | 0.00 | 0.00 | | | |
| 901009 | 8-Jul-75 | 0001 | 1.40 | 8 | 0.00 | 0.00 | 0.00 | | | |
| 901010 | 17-Jul-75 | 0001 | 1.60 | 10 | 0.00 | 0.00 | 0.00 | | | |
| 901011 | 8-Aug-75 | 0001 | 1.00 | 11 | 0.00 | 0.00 | 0.00 | | | |
| 901012 | 29-Aug-75 | 0001 | 1.00 | 12 | 0.00 | 0.00 | 0.00 | | | |
| 901013 | 4-Sep-75 | 0001 | 1.40 | 13 | 0.00 | 0.00 | 0.00 | | | |
| 901014 | 10-Sep-75 | 0001 | 1.50 | 15 | 0.00 | 0.00 | 0.00 | | | |
| 901015 | 2-Oct-75 | 0001 | 1.69 | 16 | 0.00 | 0.00 | 0.00 | | | |
| 901016 | 10-Oct-75 | 0001 | 1.84 | 18 | 0.00 | 0.00 | 0.00 | | | |
| 901017 | 26-Oct-75 | 0001 | 1.70 | 20 | 0.00 | 0.00 | 0.00 | | | |
| 901018 | 29-Oct-75 | 0001 | 1.95 | 22 | 0.00 | 0.00 | 0.00 | | | |
| 901019 | 31-Oct-75 | 0001 | 2.15 | 24 | 0.00 | 0.00 | 0.00 | | | |
| 901020 | 3-Nov-75 | 0001 | 2.35 | 26 | 0.00 | 0.00 | 0.00 | | | |
| 901021 | 4-Nov-75 | 0001 | 2.55 | 29 | 0.00 | 0.00 | 0.00 | | | |
| 901022 | 7-Nov-75 | 0001 | 2.76 | 31 | 0.00 | 0.00 | 0.00 | | | |
| 901023 | 12-Nov-75 | 0001 | 2.99 | 34 | 0.00 | 0.00 | 0.00 | | | |
| 901024 | 14-Dec-75 | 0001 | 2.35 | 37 | 0.00 | 0.00 | 0.00 | | | |
| 901025 | 22-Dec-75 | 0001 | 0.90 | 38 | 0.00 | 0.00 | 0.00 | | | |
| 901026 | 23-Dec-75 | 0001 | 2.35 | 40 | 0.00 | 0.00 | 0.00 | | | |
| 901027 | 30-Dec-75 | 0001 | 1.90 | 42 | 0.00 | 0.00 | 0.00 | | | |
| 901028 | 3-Jan-76 | 0001 | 1.74 | 44 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901029 | 7-Jan-76 | 0001 | 1.93 | 46 | 0.00 | 0.00 | 0.00 | | | |
| 901030 | 13-Jan-76 | 0001 | 2.35 | 48 | 0.00 | 0.00 | 0.00 | | | |
| 901031 | 15-Jan-76 | 0001 | 2.73 | 51 | 0.00 | 0.00 | 0.00 | | | |
| 901032 | 16-Jan-76 | 0001 | 2.76 | 53 | 0.00 | 0.00 | 0.00 | | | |
| 901033 | 19-Jan-76 | 0001 | 2.86 | 56 | 0.00 | 0.00 | 0.00 | | | |
| 901034 | 21-Jan-76 | 0001 | 2.35 | 59 | 0.00 | 0.00 | 0.00 | | | |
| 901035 | 24-Jan-76 | 0001 | 3.16 | 62 | 0.00 | 0.00 | 0.00 | | | |
| 901036 | 27-Jan-76 | 0001 | 3.11 | 65 | 0.00 | 0.00 | 0.00 | | | |
| 901037 | 29-Jan-76 | 0001 | 3.36 | 68 | 0.00 | 0.00 | 0.00 | | | |
| 901038 | 5-Feb-76 | 0001 | 2.36 | 71 | 0.00 | 0.00 | 0.00 | | | |
| 901039 | 27-Feb-76 | 0001 | 2.88 | 74 | 0.00 | 0.00 | 0.00 | | | |
| 901040 | 2-Mar-76 | 0001 | 3.39 | 77 | 0.00 | 0.00 | 0.00 | | | |
| 901041 | 5-Mar-76 | 0001 | 3.84 | 81 | 0.00 | 0.00 | 0.00 | | | |
| 901042 | 8-Mar-76 | 0001 | 10.18 | 91 | [illegible] | 0.00 | 0.00 | | | |
| 901043 | 10-Mar-76 | 0001 | 23.20 | 114 | 0.00 | 0.00 | 0.00 | | | |
| 901044 | 12-Mar-76 | 0001 | 45.18 | 159 | 0.00 | 0.00 | 0.00 | | | |
| 901045 | 23-Mar-76 | 0001 | 4.20 | 164 | 0.00 | 0.00 | 0.00 | | | |
| 902001 | 31-Mar-76 | 0002 | 1.54 | 165 | 0.00 | 0.00 | 0.00 | | | |
| 901046 | 2-Apr-76 | 0001 | 6.27 | 171 | 0.00 | 0.00 | 0.00 | | | |
| 901047 | 5-Apr-76 | 0001 | 1.92 | 173 | 0.00 | 0.00 | 0.00 | | | |
| 901048 | 7-Apr-76 | 0001 | 2.35 | 176 | 0.00 | 0.00 | 0.00 | | | |
| 901049 | 8-Apr-76 | 0001 | 2.36 | 178 | 0.00 | 0.00 | 0.00 | | | |
| 902002 | 19-Apr-76 | 0002 | 2.35 | 180 | 0.00 | 0.00 | 0.00 | | | |
| 901050 | 20-Apr-76 | 0001 | 4.20 | 185 | 0.00 | 0.00 | 0.00 | | | |
| 902003 | 21-Apr-76 | 0002 | 2.35 | 187 | 0.00 | 0.00 | 0.00 | | | |
| 901051 | 22-Apr-76 | 0001 | 10.32 | 197 | 0.00 | 0.00 | 0.00 | | | |
| 902004 | 24-Apr-76 | 0002 | 1.68 | 199 | 0.00 | 0.00 | 0.00 | | | |
| 901052 | 26-Apr-76 | 0001 | 7.34 | 206 | 0.00 | 0.00 | 0.00 | | | |
| 902005 | 28-Apr-76 | 0002 | 2.35 | 209 | 0.00 | 0.00 | 0.00 | | | |
| 902006 | 30-Apr-76 | 0002 | 2.35 | 211 | 0.00 | 0.00 | 0.00 | | | |
| 902007 | 3-May-76 | 0002 | 2.35 | 213 | 0.00 | 0.00 | 0.00 | | | |
| 901053 | 5-May-76 | 0001 | 6.52 | 220 | 0.00 | 0.00 | 0.00 | | | |
| 902008 | 5-May-76 | 0002 | 2.35 | 222 | 0.00 | 0.00 | 0.00 | | | |
| 901054 | 8-May-76 | 0001 | 7.31 | 229 | 0.00 | 0.00 | 0.00 | | | |

## SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Considered by this Study: Catastrophic Failures | Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902009 | 15-May-76 | 0002 | 4.20 | 234 | 0.00 | 0.00 | 0.00 | | | |
| 901055 | 18-May-76 | 0001 | 6.29 | 240 | 0.00 | 0.00 | 0.00 | | | |
| 902010 | 19-May-76 | 0002 | 2.35 | 242 | 0.00 | 0.00 | 0.00 | | | |
| 901056 | 21-May-76 | 0001 | 7.27 | 250 | 0.00 | 0.00 | 0.00 | | | |
| 902011 | 22-May-76 | 0002 | 4.20 | 254 | 0.00 | 0.00 | 0.00 | | | |
| 902012 | 25-May-76 | 0002 | 8.20 | 262 | 0.00 | 0.00 | 0.00 | | | |
| 901057 | 26-May-76 | 0001 | 11.86 | 274 | 0.00 | 0.00 | 0.00 | | | |
| 902013 | 1-Jun-76 | 0002 | 11.10 | 285 | 0.00 | 0.00 | 0.00 | | | |
| 901058 | 3-Jun-76 | 0001 | 12.08 | 297 | 0.00 | 0.00 | 0.00 | | | |
| 901059 | 5-Jun-76 | 0001 | 3.97 | 301 | 0.00 | 0.00 | 0.00 | | | |
| 902014 | 7-Jun-76 | 0002 | 3.16 | 304 | 0.00 | 0.00 | 0.00 | | | |
| 901060 | 8-Jun-76 | 0001 | 2.35 | 307 | 0.00 | 0.00 | 0.00 | | | |
| 901061 | 10-Jun-76 | 0001 | 2.35 | 309 | 0.00 | 0.00 | 0.00 | | | |
| 902015 | 12-Jun-76 | 0002 | 3.27 | 312 | 0.00 | 0.00 | 0.00 | | | |
| 902016 | 15-Jun-76 | 0002 | 16.70 | 329 | 0.00 | 0.00 | 0.00 | | | |
| 901062 | 16-Jun-76 | 0001 | 16.40 | 345 | 0.00 | 0.00 | 0.00 | | | |
| 901063 | 18-Jun-76 | 0001 | 64.04 | 409 | 0.00 | 0.00 | 0.00 | | | |
| 901064 | 23-Jun-76 | 0001 | 1.81 | 411 | 0.00 | 0.00 | 0.00 | | | |
| 901065 | 7-Jul-76 | 0001 | 16.91 | 428 | 0.00 | 0.00 | 0.00 | | | |
| 901066 | 9-Jul-76 | 0001 | 4.24 | 432 | 0.00 | 0.00 | 0.00 | | | |
| 902017 | 9-Jul-76 | 0002 | 16.44 | 449 | 0.00 | 0.00 | 0.00 | | | |
| 902018 | 14-Jul-76 | 0002 | 22.07 | 471 | 0.00 | 0.00 | 0.00 | | | |
| 902019 | 23-Jul-76 | 0002 | 1.68 | 472 | 0.00 | 0.00 | 0.00 | | | |
| 901067 | 26-Jul-76 | 0001 | 41.45 | 514 | 0.00 | 0.00 | 0.00 | | | |
| 902020 | 27-Jul-76 | 0002 | 33.00 | 547 | 0.00 | 0.00 | 0.00 | | | |
| 902021 | 11-Aug-76 | 0002 | 3.73 | 551 | 0.00 | 0.00 | 0.00 | | | |
| 902022 | 13-Aug-76 | 0002 | 10.00 | 561 | 0.00 | 0.00 | 0.00 | | | |
| 902023 | 17-Aug-76 | 0002 | 3.43 | 564 | 0.00 | 0.00 | 0.00 | | | |
| 902024 | 18-Aug-76 | 0002 | 3.63 | 568 | 0.00 | 0.00 | 0.00 | | | |
| 902025 | 20-Aug-76 | 0002 | 1.08 | 569 | 0.00 | 0.00 | 0.00 | | | |
| 902026 | 21-Aug-76 | 0002 | 3.77 | 573 | 0.00 | 0.00 | 0.00 | | | |
| 901068 | 23-Aug-76 | 0003 | 0.30 | 573 | 0.00 | 0.00 | 0.00 | | | |
| 902027 | 24-Aug-76 | 0002 | 2.96 | 576 | 0.00 | 0.00 | 0.00 | | | |
| 901069 | 25-Aug-76 | 0003 | 1.64 | 577 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901070 | 27-Aug-76 | 0003 | 4.20 | 582 | 0.00 | 0.00 | 0.00 | | | |
| 902028 | 30-Aug-76 | 0002 | 2.35 | 584 | 0.00 | 0.00 | 0.00 | | | |
| 902029 | 31-Aug-76 | 0002 | 8.00 | 592 | 0.00 | 0.00 | 0.00 | | | |
| 901071 | 1-Sep-76 | 0003 | 18.30 | 610 | 0.00 | 0.00 | 0.00 | | | |
| 902030 | 10-Sep-76 | 0002 | 24.03 | 634 | 0.00 | 0.00 | 0.00 | | | |
| 902031 | 12-Sep-76 | 0002 | 46.00 | 680 | 0.00 | 0.00 | 0.00 | | | |
| 901072 | 13-Sep-76 | 0003 | 17.15 | 697 | 0.00 | 0.00 | 0.00 | | | |
| 902032 | 15-Sep-76 | 0002 | 22.19 | 720 | 0.00 | 0.00 | 0.00 | | | |
| 901073 | 16-Sep-76 | 0003 | 49.53 | 769 | 0.00 | 0.00 | 0.00 | | | |
| 902033 | 18-Sep-76 | 0002 | 85.00 | 854 | 0.00 | 0.00 | 0.00 | | | |
| 901074 | 20-Sep-76 | 0003 | 26.52 | 881 | 0.00 | 0.00 | 0.00 | | | |
| 902034 | 22-Sep-76 | 0002 | 27.00 | 908 | 0.00 | 0.00 | 0.00 | | | |
| 901075 | 23-Sep-76 | 0003 | 2.96 | 911 | 0.00 | 0.00 | 0.00 | | | |
| 901076 | 24-Sep-76 | 0003 | 3.05 | 914 | 0.00 | 0.00 | 0.00 | | | |
| 902035 | 25-Sep-76 | 0002 | 30.00 | 944 | 0.00 | 0.00 | 0.00 | | | |
| 901077 | 26-Sep-76 | 0003 | 150.00 | 1,094 | 0.00 | 0.00 | 0.00 | | | |
| 901078 | 28-Sep-76 | 0003 | 300.00 | 1,394 | 0.00 | 0.00 | 0.00 | | | |
| 902036 | 29-Sep-76 | 0002 | 26.52 | 1,420 | 0.00 | 0.00 | 0.00 | | | |
| 901079 | 30-Sep-76 | 0003 | 650.00 | 2,070 | 0.00 | 0.00 | 0.00 | | | |
| 902037 | 1-Oct-76 | 0002 | 33.88 | 2,104 | 0.00 | 0.00 | 0.00 | | | |
| 901080 | 27-Oct-76 | 0003 | 28.09 | 2,132 | 0.00 | 0.00 | 0.00 | | | |
| 901081 | 2-Nov-76 | 0003 | 20.03 | 2,152 | 0.00 | 0.00 | 0.00 | | | |
| 901082 | 10-Nov-76 | 0003 | 20.00 | 2,172 | 0.00 | 0.00 | 0.00 | | | |
| 901083 | 20-Nov-76 | 0003 | 2.35 | 2,175 | 0.00 | 0.00 | 0.00 | | | |
| 901084 | 24-Nov-76 | 0003 | 2.99 | 2,178 | 0.00 | 0.00 | 0.00 | | | |
| 901085 | 27-Nov-76 | 0003 | 4.23 | 2,182 | 0.00 | 0.00 | 0.00 | | | |
| 901086 | 30-Nov-76 | 0003 | 11.72 | 2,193 | 0.00 | 0.00 | 0.00 | | | |
| 902038 | 5-Dec-76 | 0002 | 1.08 | 2,195 | 0.00 | 0.00 | 0.00 | | | |
| 902039 | 8-Dec-76 | 0002 | 3.71 | 2,198 | 0.00 | 0.00 | 0.00 | | | |
| 902040 | 11-Dec-76 | 0002 | 4.20 | 2,202 | 0.00 | 0.00 | 0.00 | | | |
| 902041 | 14-Dec-76 | 0002 | 2.33 | 2,205 | 0.00 | 0.00 | 0.00 | | | |
| 902042 | 15-Dec-76 | 0002 | 8.20 | 2,213 | 0.00 | 0.00 | 0.00 | | | |
| 901087 | 16-Dec-76 | 0003 | 11.72 | 2,225 | 0.00 | 0.00 | 0.00 | | | |
| 902043 | 17-Dec-76 | 0002 | 33.20 | 2,258 | 0.00 | 0.00 | 0.00 | | | |

# SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901088 | 18-Dec-76 | 0001 | 6.20 | 2,264 | 0.00 | 0.00 | 0:00 | | | |
| 902044 | 20-Dec-76 | 0002 | 19.60 | 2,284 | 0.00 | 0.00 | 0.00 | | | |
| 901089 | 27-Dec-76 | 0003 | 8.00 | 2,292 | 0.00 | 0.00 | 0.00 | | | |
| 901090 | 28-Dec-76 | 0003 | 17.69 | 2,309 | 0.00 | 0.00 | 0.00 | | | |
| 901091 | 31-Dec-76 | 0003 | 64.00 | 2,373 | 0.00 | 0.00 | 0.00 | | | |
| 901092 | 3-Jan-77 | 0003 | 21.50 | 2,395 | 0.00 | 0.00 | 0.00 | | | |
| 901093 | 5-Jan-77 | 0003 | 18.08 | 2,413 | 0.00 | 0.00 | 0.00 | | | |
| 901094 | 6-Jan-77 | 0003 | 15.65 | 2,429 | 0.00 | 0.00 | 0.00 | | | |
| 901095 | 7-Jan-77 | 0003 | 26.44 | 2,455 | 5.00 | 0.00 | 0.00 | | | |
| 901096 | 11-Jan-77 | 0003 | 28.63 | 2,484 | 9.60 | 0.00 | 0.00 | | | |
| 902045 | 12-Jan-77 | 0002 | 1.06 | 2,485 | 0.00 | 0.00 | 0.00 | | | |
| 902046 | 13-Jan-77 | 0002 | 405.01 | 2,890 | 0.00 | 0.00 | 0.00 | | | |
| 902047 | 17-Jan-77 | 0002 | 1.62 | 2,891 | 0.00 | 0.00 | 0.00 | | | |
| 902048 | 18-Jan-77 | 0002 | 4.23 | 2,896 | 0.00 | 0.00 | 0.00 | | | |
| 901097 | 28-Jan-77 | 0003 | 4.25 | 2,900 | 0.00 | 0.00 | 0.00 | | | |
| 901098 | 29-Jan-77 | 0003 | 64.12 | 2,964 | 21.12 | 0.00 | 0.00 | | | |
| 901099 | 31-Jan-77 | 0003 | 39.80 | 3,004 | 15.30 | 0.00 | 0.00 | | | |
| 902049 | 6-Feb-77 | 0002 | 3.23 | 3,007 | 0.00 | 0.00 | 0.00 | | | |
| 901100 | 11-Feb-77 | 0003 | 14.18 | 3,021 | 0.00 | 0.00 | 0.00 | | | |
| 901101 | 13-Feb-77 | 0003 | 4.31 | 3,026 | 0.00 | 0.00 | 0.00 | | | |
| 901102 | 14-Feb-77 | 0003 | 29.85 | 3,055 | 0.00 | 0.00 | 0.00 | | | |
| 901103 | 18-Feb-77 | 0003 | 23.01 | 3,078 | 3.51 | 0.00 | 0.00 | | | |
| 902050 | 20-Feb-77 | 0002 | 6.00 | 3,084 | 0.00 | 0.00 | 0.00 | | | |
| 902051 | 22-Feb-77 | 0002 | 2.37 | 3,087 | 0.00 | 0.00 | 0.00 | | | |
| 902052 | 23-Feb-77 | 0002 | 2.37 | 3,089 | 0.00 | 0.00 | 0.00 | | | |
| 902053 | 25-Feb-77 | 0002 | 2.35 | 3,091 | 0.00 | 0.00 | 0.00 | | | |
| 901104 | 26-Feb-77 | 0003 | 10.61 | 3,102 | 0.00 | 0.00 | 0.00 | | | |
| 902054 | 28-Feb-77 | 0002 | 11.42 | 3,114 | 0.00 | 0.00 | 0.00 | | | |
| 901105 | 3-Mar-77 | 0003 | 35.33 | 3,149 | 15.83 | 0.00 | 0.00 | | | |
| 901106 | 6-Mar-77 | 0003 | 86.43 | 3,235 | 0.00 | 0.00 | 0.00 | | | |
| 901107 | 9-Mar-77 | 0003 | 8.50 | 3,244 | 0.00 | 0.00 | 0.00 | | | |
| 901108 | 10-Mar-77 | 0003 | 29.49 | 3,273 | 4.99 | 0.00 | 0.00 | | | |
| 901109 | 12-Mar-77 | 0003 | 80.49 | 3,354 | 60.99 | 0.00 | 0.00 | | | |
| 902055 | 14-Mar-77 | 0002 | 2.35 | 3,356 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902056 | 16-Mar-77 | 0002 | 24.50 | 3,381 | 5.00 | 0.00 | 0.00 | | | |
| 902057 | 18-Mar-77 | 0002 | 22.01 | 3,403 | 0.00 | 0.00 | 0.00 | | | |
| 902058 | 21-Mar-77 | 0002 | 540.00 | 3,943 | 0.00 | 0.00 | 0.00 | | | |
| 901110 | 24-Mar-77 | 0003 | 74.07 | 4,017 | 0.00 | 0.00 | 0.00 | X | | |
| 902059 | 27-Apr-77 | 0002 | 4.13 | 4,021 | 0.00 | 0.00 | 0.00 | | | |
| 902060 | 29-Apr-77 | 0002 | 10.01 | 4,031 | 0.00 | 0.00 | 0.00 | | | |
| 902061 | 2-May-77 | 0002 | 80.01 | 4,111 | 0.00 | 0.00 | 0.00 | | | |
| 902062 | 5-May-77 | 0002 | 29.93 | 4,141 | 0.00 | 0.00 | 0.00 | | | |
| 902063 | 10-May-77 | 0002 | 100.00 | 4,241 | 0.00 | 0.00 | 0.00 | | | |
| 902064 | 12-May-77 | 0002 | 104.02 | 4,345 | 0.00 | 0.00 | 0.00 | | | |
| 902065 | 14-May-77 | 0002 | 80.00 | 4,425 | 10.00 | 0.00 | 0.00 | | | |
| 901111 | 15-May-77 | 0004 | 2.35 | 4,427 | 0.00 | 0.00 | 0.00 | | | |
| 901112 | 17-May-77 | 0004 | 2.35 | 4,429 | 0.00 | 0.00 | 0.00 | | | |
| 901113 | 20-May-77 | 0004 | 17.34 | 4,447 | 0.00 | 0.00 | 0.00 | | | |
| 901114 | 23-May-77 | 0004 | 7.70 | 4,455 | 0.00 | 0.00 | 0.00 | | | |
| 901115 | 18-Jun-77 | 0004 | 100.01 | 4,555 | 0.00 | 0.00 | 0.00 | | | |
| 901116 | 21-Jun-77 | 0004 | 73.23 | 4,628 | 0.00 | 0.00 | 0.00 | | | |
| 901117 | 28-Jun-77 | 0004 | 0.54 | 4,628 | 0.00 | 0.00 | 0.00 | | | |
| 901118 | 29-Jun-77 | 0004 | 5.00 | 4,633 | 0.00 | 0.00 | 0.00 | | | |
| 901119 | 1-Jul-77 | 0004 | 31.74 | 4,665 | 0.00 | 0.00 | 0.00 | | | |
| 901120 | 2-Jul-77 | 0004 | 238.70 | 4,904 | 0.00 | 0.00 | 0.00 | | | |
| 901121 | 5-Jul-77 | 0004 | 4.65 | 4,908 | 0.00 | 0.00 | 0.00 | | | |
| 901122 | 6-Jul-77 | 0004 | 6.06 | 4,914 | 0.00 | 0.00 | 0.00 | | | |
| 901123 | 7-Jul-77 | 0004 | 149.48 | 5,064 | 0.00 | 0.00 | 0.00 | | | |
| 902066 | 13-Jul-77 | 0002 | 10.01 | 5,074 | 0.00 | 0.00 | 0.00 | | | |
| 902067 | 15-Jul-77 | 0002 | 30.00 | 5,104 | 0.00 | 0.00 | 0.00 | | | |
| 902068 | 18-Jul-77 | 0002 | 5.06 | 5,109 | 0.00 | 0.00 | 0.00 | | | |
| 902069 | 19-Jul-77 | 0002 | 35.01 | 5,144 | 9.00 | 0.00 | 0.00 | | | |
| 902070 | 21-Jul-77 | 0002 | 29.31 | 5,173 | 5.70 | 0.00 | 0.00 | | | |
| 901124 | 25-Jul-77 | 0004 | 6.64 | 5,180 | 0.00 | 0.00 | 0.00 | | | |
| 901125 | 27-Jul-77 | 0004 | 425.01 | 5,605 | 0.00 | 0.00 | 0.00 | | | |
| 901126 | 28-Jul-77 | 0004 | 415.00 | 6,020 | 10.00 | 0.00 | 0.00 | | | |
| 901127 | 30-Jul-77 | 0004 | 328.30 | 6,348 | 0.00 | 0.00 | 0.00 | | | |
| 901128 | 1-Aug-77 | 0004 | 424.94 | 6,773 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Considered by this Study: Catastrophic Failures | Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901129 | 4-Aug-77 | 0004 | 257.10 | 7,030 | 0.00 | 0.00 | 0.00 | | | |
| 901130 | 5-Aug-77 | 0004 | 425.00 | 7,455 | 0.00 | 0.00 | 0.00 | | | |
| 901131 | 8-Aug-77 | 0004 | 425.00 | 7,880 | 0.00 | 0.00 | 0.00 | | | |
| 902071 | 9-Aug-77 | 0002 | 13.40 | 7,894 | 0.00 | 0.00 | 0.00 | | | |
| 902072 | 10-Aug-77 | 0002 | 4.41 | 7,898 | 0.00 | 0.00 | 0.00 | | | |
| 902073 | 15-Aug-77 | 0002 | 155.50 | 8,054 | 0.00 | 0.00 | 0.00 | | | |
| 902074 | 18-Aug-77 | 0002 | 7.05 | 8,061 | 0.00 | 0.00 | 0.00 | | | |
| 902075 | 20-Aug-77 | 0002 | 21.71 | 8,082 | 0.00 | 0.00 | 0.00 | | | |
| 902076 | 24-Aug-77 | 0002 | 230.39 | 8,313 | 5.00 | 0.00 | 0.00 | | | |
| 901132 | 25-Aug-77 | 0004 | 30.00 | 8,343 | 0.00 | 0.00 | 0.00 | | | |
| 902077 | 26-Aug-77 | 0002 | 321.00 | 8,664 | 301.01 | 0.00 | 0.00 | | | |
| 901133 | 27-Aug-77 | 0004 | 48.21 | 8,712 | 10.00 | 0.00 | 0.00 | X | | |
| 902078 | 1-Sep-77 | 0002 | 335.99 | 9,048 | 10.00 | 0.00 | 0.00 | | | |
| 901134 | 2-Sep-77 | 0004 | 76.80 | 9,125 | 45.80 | 0.00 | 0.00 | | | |
| 901135 | 6-Sep-77 | 0004 | 335.00 | 9,460 | 0.00 | 0.00 | 0.00 | | | |
| 901136 | 8-Sep-77 | 0004 | 300.22 | 9,760 | 100.00 | 0.00 | 0.00 | X | | |
| 902079 | 26-Sep-77 | 0002 | 3.05 | 9,763 | 0.00 | 0.00 | 0.00 | | | |
| 902080 | 28-Sep-77 | 0002 | 9.05 | 9,772 | 0.00 | 0.00 | 0.00 | | | |
| 902081 | 1-Oct-77 | 0002 | 15.01 | 9,787 | 0.00 | 0.00 | 0.00 | | | |
| 902082 | 9-Oct-77 | 0002 | 40.00 | 9,827 | 0.00 | 0.00 | 0.00 | | | |
| 902083 | 11-Oct-77 | 0002 | 34.94 | 9,862 | 0.00 | 0.00 | 0.00 | | | |
| 902084 | 13-Oct-77 | 0002 | 85.00 | 9,947 | 0.00 | 0.00 | 0.00 | | | |
| 902085 | 17-Oct-77 | 0002 | 2.35 | 9,949 | 0.00 | 0.00 | 0.00 | | | |
| 902086 | 20-Oct-77 | 0002 | 2.35 | 9,952 | 0.00 | 0.00 | 0.00 | | | |
| 902087 | 26-Oct-77 | 0002 | 2.35 | 9,954 | 0.00 | 0.00 | 0.00 | | | |
| 902088 | 27-Oct-77 | 0002 | 1.73 | 9,956 | 0.00 | 0.00 | 0.00 | | | |
| 902089 | 28-Oct-77 | 0002 | 55.01 | 10,011 | 0.00 | 0.00 | 0.00 | | | |
| 901137 | 31-Oct-77 | 0103 | 19.32 | 10,030 | 0.00 | 0.00 | 0.00 | | | |
| 902090 | 1-Nov-77 | 0002 | 48.63 | 10,079 | 0.00 | 0.00 | 0.00 | | | |
| 902091 | 3-Nov-77 | 0002 | 100.00 | 10,179 | 0.00 | 0.00 | 0.00 | | | |
| 901138 | 4-Nov-77 | 0103 | 100.00 | 10,279 | 0.00 | 0.00 | 0.00 | | | |
| 902092 | 6-Nov-77 | 0002 | 229.97 | 10,509 | 4.00 | 0.00 | 0.00 | | | |
| 901139 | 7-Nov-77 | 0103 | 54.83 | 10,564 | 0.00 | 0.00 | 0.00 | | | |
| 902093 | 9-Nov-77 | 0002 | 364.16 | 10,928 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901140 | 10-Nov-77 | 0103 | 100.00 | 11,028 | 0.00 | 0.00 | 0.00 | | | |
| 901141 | 11-Nov-77 | 0103 | 400.00 | 11,428 | 0.00 | 0.00 | 0.00 | | | |
| 901142 | 13-Nov-77 | 0103 | 400.00 | 11,828 | 0.00 | 0.00 | 0.00 | | | |
| 902094 | 14-Nov-77 | 0002 | 200.00 | 12,028 | 0.00 | 0.00 | 0.00 | | | |
| 902095 | 17-Nov-77 | 0002 | 51.09 | 12,079 | 0.00 | 0.00 | 0.00 | | | |
| 901143 | 21-Nov-7 | 0103 | 100.00 | 12,179 | 0.00 | 0.00 | 0.00 | | | |
| 901144 | 23-Nov-77 | 0103 | 400.00 | 12,579 | 0.00 | 0.00 | 0.00 | | | |
| 901145 | 26-Nov-77 | 0103 | 350.00 | 12,929 | 0.00 | 0.00 | 0.00 | | | |
| 902096 | 28-Nov-77 | 0002 | 91.04 | 13,020 | 0.00 | 0.00 | 0.00 | | | |
| 901146 | 29-Nov-77 | 0103 | 400.00 | 13,420 | 0.00 | 0.00 | 0.00 | | | |
| 901147 | 1-Dec-77 | 0103 | 31.36 | 13,451 | 0.00 | 0.00 | 0.00 | | | |
| 901148 | 12-Dec-77 | 0002 | 2.35 | 13,454 | 0.00 | 0.00 | 0.00 | | | |
| 901149 | 13-Dec-77 | 0002 | 10.01 | 13,464 | 0.00 | 0.00 | 0.00 | | | |
| 901150 | 15-Dec-77 | 0002 | 9.83 | 13,473 | 0.00 | 0.00 | 0.00 | | | |
| 901151 | 17-Dec-77 | 0002 | 9.00 | 13,482 | 0.00 | 0.00 | 0.00 | | | |
| 901152 | 19-Dec-77 | 0002 | 9.00 | 13,491 | 0.00 | 0.00 | 0.00 | | | |
| 901153 | 20-Dec-77 | 0002 | 9.00 | 13,500 | 0.00 | 0.00 | 0.00 | | | |
| 901154 | 22-Dec-77 | 0002 | 8.00 | 13,508 | 0.00 | 0.00 | 0.00 | | | |
| 901155 | 4-Jan-78 | 0002 | 12.00 | 13,520 | 0.00 | 0.00 | 0.00 | | | |
| 901156 | 5-Jan-78 | 0002 | 100.00 | 13,620 | 0.00 | 0.00 | 0.00 | | | |
| 901157 | 9-Jan-78 | 0002 | 100.00 | 13,720 | 0.00 | 0.00 | 0.00 | | | |
| 902097 | 17-Jan-78 | 2001 | 49.01 | 13,769 | 0.00 | 0.00 | 0.00 | | | |
| 902098 | 25-Jan-78 | 2001 | 71.00 | 13,840 | 0.00 | 0.00 | 0.00 | | | |
| 902099 | 30-Jan-78 | 2002 | 60.00 | 13,900 | 0.00 | 0.00 | 0.00 | | | |
| 902100 | 2-Feb-78 | 2002 | 2.89 | 13,903 | 0.00 | 0.00 | 0.00 | | | |
| 901158 | 8-Feb-78 | 0002 | 100.00 | 14,003 | 0.00 | 0.00 | 0.00 | | | |
| 902101 | 9-Feb-78 | 2002 | 26.64 | 14,030 | 0.00 | 0.00 | 0.00 | | | |
| 901159 | 10-Feb-78 | 0002 | 96.33 | 14,126 | 0.00 | 0.00 | 0.00 | | | |
| 901160 | 12-Feb-78 | 0002 | 4.04 | 14,130 | 0.00 | 0.00 | 0.00 | | | |
| 901161 | 14-Feb-78 | 0002 | 4.25 | 14,135 | 0.05 | 0.00 | 0.00 | | | |
| 901162 | 15-Feb-78 | 0002 | 11.32 | 14,146 | 0.92 | 0.00 | 0.00 | | | |
| 902102 | 15-Feb-78 | 2002 | 41.49 | 14,187 | 0.00 | 0.00 | 0.00 | | | |
| 901163 | 17-Feb-78 | 0002 | 3.57 | 14,191 | 0.00 | 0.00 | 0.00 | | | |
| 901164 | 21-Feb-78 | 0002 | 6.08 | 14,197 | 0.00 | 0.00 | 0.00 | | | |

## SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902103 | 22-Feb-78 | 2002 | 60.00 | 14,257 | 0.00 | 0.00 | 0.00 | | | |
| 902*04 | 5-Mar-78 | 2003 | 60.04 | 14,317 | 0.00 | 0.00 | 0.00 | | | |
| 902105 | 8-Mar-78 | 2003 | 60.04 | 14,377 | 0.00 | 0.00 | 0.00 | | | |
| 901165 | 13-Mar-78 | 0002 | 2.35 | 14,379 | 0.00 | 0.00 | 0.00 | | | |
| 901166 | 15-Mar-78 | 0002 | 2.03 | 14,382 | 0.00 | 0.00 | 0.00 | | | |
| 901167 | 17-Mar-78 | 0002 | 3.83 | 14,385 | 0.00 | 0.00 | 0.00 | | | |
| 901168 | 20-Mar-78 | 0002 | 7.95 | 14,393 | 0.00 | 0.00 | 0.00 | | | |
| 901169 | 21-Mar-78 | 0002 | 210.97 | 14,604 | 0.00 | 0.00 | 0.00 | | | |
| 901170 | 25-Mar-78 | 0002 | 310.74 | 14,915 | 0.00 | 0.00 | 0.00 | | | |
| 901171 | 27-Mar-78 | 0002 | 10.71 | 14,926 | 0.11 | 0.00 | 0.00 | | | |
| 901172 | 29-Mar-78 | 0002 | 360.03 | 15,286 | 0.00 | 0.00 | 0.00 | | | |
| 901173 | 31-Mar-78 | 0002 | 201.17 | 15,487 | 0.00 | 0.00 | 0.00 | | | |
| 902106 | 13-Apr-78 | 0101 | 5.90 | 15,493 | 0.00 | 0.00 | 0.00 | | | |
| 902107 | 16-Apr-78 | 0101 | 8.83 | 15,502 | 0.00 | 0.00 | 0.00 | | | |
| 902108 | 19-Apr-78 | 0101 | 8.55 | 15,510 | 0.00 | 0.00 | 0.00 | | | |
| 902109 | 21-Apr-78 | 0101 | 2.99 | 15,513 | 0.00 | 0.00 | 0.00 | | | |
| SF01-02A | 21-Apr-78 | 2001 | 1.19 | 15,514 | 0.00 | 0.00 | 0.00 | | | |
| SF01-02B | 21-Apr-78 | 2003 | 1.04 | 15,515 | 0.00 | 0.00 | 0.00 | | | |
| SF01-02C | 21-Apr-78 | 2002 | 0.98 | 15,516 | 0.00 | 0.00 | 0.00 | | | |
| 901174 | 4-May-78 | 0005 | 47.97 | 15,564 | 0.00 | 0.00 | 0.00 | | | |
| 901175 | 6-May-78 | 0005 | 119.07 | 15,683 | 114.94 | 0.00 | 0.00 | | | |
| 901176 | 8-May-78 | 0005 | 32.03 | 15,715 | 27.89 | 0.00 | 0.00 | | | |
| 901177 | 10-May-78 | 0005 | 520.00 | 16,235 | 515.97 | 0.00 | 0.00 | | | |
| 901178 | 13-May-78 | 0005 | 4.27 | 16,240 | 0.00 | 0.00 | 0.00 | | | |
| 901179 | 16-May-78 | 0005 | 122.90 | 16,363 | 90.08 | 0.00 | 0.00 | | | |
| SF02-01A | 19-May-78 | 2001 | 18.84 | 16,381 | 0.00 | 0.00 | 0.00 | | | |
| SF02-01B | 19-May-78 | 2003 | 20.52 | 16,402 | 0.00 | 0.00 | 0.00 | | | |
| SF02-01C | 19-May-78 | 2002 | 20.42 | 16,422 | 0.00 | 0.00 | 0.00 | | | |
| 901180 | 28-May-78 | 0005 | 1.41 | 16,424 | 0.00 | 0.00 | 0.00 | | | |
| 901181 | 30-May-78 | 0005 | 20.00 | 16,444 | 0.00 | 0.00 | 0.00 | | | |
| 901182 | 2-Jun-78 | 0005 | 7.82 | 16,452 | 3.88 | 0.00 | 0.00 | | | |
| 901183 | 5-Jun-78 | 0005 | 51.00 | 16,503 | 0.30 | 0.00 | 0.00 | | | |
| 902110 | 6-Jun-78 | 0101 | 2.35 | 16,505 | 0.00 | 0.00 | 0.00 | | | |
| 902111 | 8-Jun-78 | 0101 | 4.53 | 16,510 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902112 | 10-Jun-78 | 0101 | 5.74 | 16,515 | 0.00 | 0.00 | 0.00 | | | |
| SF03-01A | 15-Jun-78 | 2001 | 41.82 | 16,557 | 0.00 | 0.00 | 0.00 | | | |
| SF03-01B | 15-Jun-78 | 2003 | 42.24 | 16,599 | 0.00 | 0.00 | 0.00 | | | |
| SF03-01C | 15-Jun-78 | 2002 | 42.63 | 16,642 | 0.00 | 0.00 | 0.00 | | | |
| 902113 | 22-Jun-78 | 0101 | 25.00 | 16,667 | 4.20 | 0.00 | 0.00 | | | |
| 902114 | 24-Jun-78 | 0101 | 281.03 | 16,948 | 0.83 | 0.00 | 0.00 | | | |
| 902115 | 27-Jun-78 | 0101 | 299.98 | 17,248 | 0.00 | 0.00 | 0.00 | | | |
| 902116 | 29-Jun-78 | 0101 | 10.85 | 17,259 | 0.00 | 0.00 | 0.00 | | | |
| SF04-01A | 7-Jul-78 | 2001 | 103.88 | 17,363 | 0.00 | 0.00 | 0.00 | | | |
| SF04-01B | 7-Jul-78 | 2003 | 93.70 | 17,456 | 0.00 | 0.00 | 0.00 | | | |
| SF04-01C | 7-Jul-78 | 2002 | 103.63 | 17,560 | 0.00 | 0.00 | 0.00 | | | |
| 902117 | 8-Jul-78 | 0101 | 6.08 | 17,566 | 0.00 | 0.00 | 0.00 | | | |
| 902118 | 10-Jul-78 | 0101 | 6.84 | 17,573 | 0.00 | 0.00 | 0.00 | | | |
| 901184 | 14-Jul-78 | 0005 | 30.00 | 17,603 | 6.00 | 0.00 | 0.00 | | | |
| 902119 | 14-Jul-78 | 0101 | 166.69 | 17,770 | 50.69 | 0.00 | 0.00 | | | |
| 902120 | 18-Jul-78 | 0101 | 41.81 | 17,811 | 21.01 | 0.00 | 0.00 | | | |
| 901185 | 12-Aug-78 | 0005 | 50.00 | 17,861 | 9.20 | 0.00 | 0.00 | | | |
| 901186 | 13-Aug-78 | 0005 | 240.39 | 18,102 | 199.59 | 0.00 | 0.00 | | | |
| 901187 | 18-Aug-78 | 0005 | 150.00 | 18,252 | 103.00 | 0.00 | 0.00 | | | |
| 901188 | 20-Aug-78 | 0005 | 300.00 | 18,552 | 274.20 | 0.00 | 0.00 | | | |
| 902121 | 22-Aug-78 | 2002 | 7.16 | 18,559 | 0.00 | 0.00 | 0.00 | | | |
| 901189 | 23-Aug-78 | 0005 | 64.64 | 18,624 | 60.42 | 0.00 | 0.00 | | | |
| 902122 | 24-Aug-78 | 2002 | 300.00 | 18,924 | 257.00 | 0.00 | 0.00 | | | |
| 901190 | 26-Aug-78 | 0005 | 137.83 | 19,061 | 133.77 | 0.00 | 0.00 | | | |
| 902123 | 27-Aug-78 | 2002 | 100.00 | 19,161 | 57.00 | 0.00 | 0.00 | | | |
| 901191 | 28-Aug-78 | 0005 | 300.00 | 19,461 | 295.92 | 0.00 | 0.00 | | | |
| 902124 | 29-Aug-78 | 2002 | 266.82 | 19,728 | 223.82 | 0.00 | 0.00 | | | |
| 901192 | 30-Aug-78 | 0005 | 300.00 | 20,028 | 295.99 | 0.00 | 0.00 | | | |
| 902125 | 31-Aug-78 | 2002 | 72.02 | 20,100 | 29.02 | 0.00 | 0.00 | | | |
| 902126 | 1-Sep-78 | 2002 | 300.00 | 20,400 | 247.00 | 0.00 | 0.00 | | | |
| 901193 | 2-Sep-78 | 0005 | 300.00 | 20,700 | 295.88 | 0.00 | 0.00 | | | |
| 902127 | 5-Sep-78 | 2002 | 111.56 | 20,812 | 68.56 | 0.00 | 0.00 | | | |
| 901194 | 6-Sep-78 | 0005 | 310.11 | 21,122 | 306.05 | 0.00 | 0.00 | | | |
| 902128 | 6-Sep-78 | 2002 | 300.00 | 21,422 | 247.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901195 | 7-Sep-78 | 0005 | 520.00 | 21,942 | 515.92 | 0.00 | 0.00 | | | |
| 902129 | 8-Sep-78 | 2002 | 300.00 | 22,242 | 247.00 | 0.00 | 0.00 | | | |
| 901196 | 9-Sep-78 | 0005 | 520.00 | 22,762 | 515.92 | 0.00 | 0.00 | | | |
| 901197 | 11-Sep-78 | 0005 | 520.00 | 23,282 | 515.97 | 0.00 | 0.00 | | | |
| 901198 | 13-Sep-78 | 0005 | 520.00 | 23,802 | 515.91 | 0.00 | 0.00 | | | |
| 902130 | 14-Sep-78 | 2002 | 301.50 | 24,103 | 258.50 | 0.00 | 0.00 | | | |
| 901199 | 15-Sep-78 | 0005 | 520.00 | 24,623 | 355.94 | 0.00 | 0.00 | | | |
| 901200 | 18-Sep-78 | 0005 | 289.10 | 24,913 | 285.00 | 0.00 | 0.00 | | | |
| 902131 | 19-Sep-78 | 2002 | 300.04 | 25,213 | 132.50 | 0.00 | 0.00 | | | |
| 901201 | 25-Sep-78 | 0005 | 3.05 | 25,216 | 0.00 | 0.00 | 0.00 | | | |
| 901202 | 26-Sep-78 | 0005 | 138.51 | 25,354 | 134.41 | 0.00 | 0.00 | | | |
| 901203 | 28-Sep-78 | 0005 | 300.00 | 25,654 | 295.84 | 0.00 | 0.00 | | | |
| 901204 | 1-Oct-78 | 0005 | 300.00 | 25,954 | 0.00 | 0.00 | 0.00 | | | |
| 902132 | 3-Oct-78 | 0006 | 2.36 | 25,957 | 0.00 | 0.00 | 0.00 | | | |
| 901205 | 9-Oct-78 | 0005 | 300.00 | 26,257 | 219.00 | 0.00 | 0.00 | | | |
| 901206 | 11-Oct-78 | 0005 | 300.00 | 26,557 | 0.00 | 0.00 | 0.00 | | | |
| 901207 | 16-Oct-78 | 0005 | 2.35 | 26,559 | 0.00 | 0.00 | 0.00 | | | |
| 901208 | 17-Oct-78 | 0005 | 4.88 | 26,564 | 0.00 | 0.00 | 0.00 | | | |
| 901209 | 19-Oct-78 | 0005 | 100.00 | 26,664 | 0.00 | 0.00 | 0.00 | | | |
| 901210 | 20-Oct-78 | 0005 | 300.00 | 26,964 | 9.50 | 0.00 | 0.00 | | | |
| 902133 | 20-Oct-78 | 2002 | 50.00 | 27,014 | 0.00 | 0.00 | 0.00 | | | |
| 901211 | 23-Oct-78 | 0005 | 520.00 | 27,534 | 0.00 | 0.00 | 0.00 | | | |
| 901212 | 25-Oct-78 | 0005 | 300.00 | 27,834 | 199.00 | 0.00 | 0.00 | | | |
| 901213 | 27-Oct-78 | 0005 | 1.30 | 27,835 | 0.00 | 0.00 | 0.00 | | | |
| 901214 | 28-Oct-78 | 0005 | 290.38 | 28,125 | 189.38 | 0.00 | 0.00 | | | |
| 902134 | 28-Oct-78 | 2002 | 100.00 | 28,225 | 0.00 | 0.00 | 0.00 | | | |
| 901215 | 30-Oct-78 | 0005 | 823.00 | 29,048 | 0.00 | 0.00 | 0.00 | | | |
| 901216 | 2-Nov-78 | 0005 | 3.57 | 29,052 | 0.00 | 0.00 | 0.00 | | | |
| 902135 | 2-Nov-78 | 2002 | 2.79 | 29,055 | 0.00 | 0.00 | 0.00 | | | |
| 901217 | 3-Nov-78 | 0005 | 520.00 | 29,575 | 0.00 | 0.00 | 0.00 | | | |
| 902136 | 3-Nov-78 | 2002 | 285.00 | 29,860 | 226.50 | 0.00 | 0.00 | | | |
| 750001 | 7-Nov-78 | 0201 | 2.35 | 29,862 | 0.00 | 0.00 | 0.00 | | | |
| 901218 | 7-Nov-78 | 0005 | 520.00 | 30,382 | 0.00 | 0.00 | 0.00 | | | |
| 902137 | 7-Nov-78 | 2002 | 50.00 | 30,432 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901219 | 9-Nov-78 | 0005 | 520.00 | 30,952 | 0.00 | 0.00 | 0.00 | | | |
| 902138 | 9-Nov-78 | 2002 | 100.00 | 31,052 | 0.00 | 0.00 | 0.00 | | | |
| 750002 | 10-Nov-78 | 0201 | 4.00 | 31,056 | 0.00 | 0.00 | 0.00 | | | |
| 901220 | 11-Nov-78 | 0005 | 197.80 | 31,254 | 0.00 | 0.00 | 0.00 | | | |
| 902139 | 13-Nov-78 | 2002 | 200.00 | 31,454 | 0.00 | 0.00 | 0.00 | | | |
| 901221 | 15-Nov-78 | 0005 | 665.00 | 32,119 | 0.00 | 0.00 | 0.00 | | | |
| 902140 | 15-Nov-78 | 2002 | 200.00 | 32,319 | 19.00 | 0.00 | 0.00 | | | |
| 902141 | 17-Nov-78 | 2002 | 300.00 | 32,619 | 185.96 | 0.00 | 0.00 | | | |
| 750003 | 22-Nov-78 | 0201 | 15.00 | 32,634 | 0.00 | 0.00 | 0.00 | | | |
| 750004 | 29-Nov-78 | 0201 | 50.00 | 32,684 | 9.00 | 0.00 | 0.00 | | | |
| 902142 | 2-Dec-78 | 2002 | 2.71 | 32,687 | 0.00 | 0.00 | 0.00 | | | |
| 902143 | 3-Dec-78 | 2002 | 2.81 | 32,689 | 0.00 | 0.00 | 0.00 | | | |
| 902144 | 4-Dec-78 | 2002 | 36.29 | 32,726 | 29.02 | 0.00 | 0.00 | | | |
| 750005 | 5-Dec-78 | 0201 | 1.50 | 32,727 | 0.00 | 0.00 | 0.00 | | | |
| 901222 | 5-Dec-78 | 0007 | 4.35 | 32,732 | 0.00 | 0.00 | 0.00 | X | | |
| 750006 | 7-Dec-78 | 0201 | 40.90 | 32,773 | 0.00 | 0.00 | 0.00 | | | |
| 902145 | 8-Dec-78 | 2002 | 68.61 | 32,841 | 35.65 | 0.00 | 0.00 | | | |
| 750007 | 9-Dec-78 | 0201 | 300.00 | 33,141 | 0.00 | 0.00 | 0.00 | | | |
| 902146 | 11-Dec-78 | 2002 | 520.00 | 33,661 | 427.00 | 0.00 | 0.00 | | | |
| 750008 | 13-Dec-78 | 0201 | 300.00 | 33,961 | 0.00 | 0.00 | 0.00 | | | |
| 902147 | 15-Dec-78 | 2002 | 260.16 | 34,221 | 256.16 | 0.00 | 0.00 | | | |
| 750009 | 16-Dec-78 | 0201 | 35.00 | 34,256 | 10.00 | 0.00 | 0.00 | | | |
| 901223 | 19-Dec-78 | 2001 | 1.61 | 34,258 | 0.00 | 0.00 | 0.00 | | | |
| 750010 | 20-Dec-78 | 0201 | 264.30 | 34,522 | 244.00 | 0.00 | 0.00 | | | |
| 901224 | 23-Dec-78 | 2001 | 60.01 | 34,582 | 56.03 | 0.00 | 0.00 | | | |
| 901225 | 27-Dec-78 | 2001 | 255.63 | 34,838 | 222.57 | 0.00 | 0.00 | X | | |
| 750011 | 30-Jan-79 | 0201 | 1.40 | 34,839 | 0.00 | 0.00 | 0.00 | | | |
| 750012 | 2-Feb-79 | 0201 | 1.50 | 34,841 | 0.00 | 0.00 | 0.00 | | | |
| 750013 | 4-Feb-79 | 0201 | 25.00 | 34,866 | 9.50 | 0.00 | 0.00 | | | |
| 901226 | 5-Feb-79 | 2003 | 1.40 | 34,867 | 0.00 | 0.00 | 0.00 | | | |
| 750014 | 8-Feb-79 | 0201 | 1.50 | 34,869 | 0.00 | 0.00 | 0.00 | | | |
| 750015 | 10-Feb-79 | 0201 | 25.00 | 34,894 | 9.52 | 0.00 | 0.00 | | | |
| 750016 | 12-Feb-79 | 0201 | 300.00 | 35,194 | 0.00 | 0.00 | 0.00 | | | |
| 750017 | 24-Feb-79 | 0201 | 41.00 | 35,235 | 25.62 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750018 | 2-Mar-79 | 0201 | 107.81 | 35,342 | 42.33 | 0.00 | 0.00 | | | |
| 750019 | 4-Mar-79 | 0201 | 300.00 | 35,642 | 285.56 | 0.00 | 0.00 | | | |
| 901227 | 4-Mar-79 | 2003 | 4.35 | 35,647 | 0.00 | 0.00 | 0.00 | | | |
| 901228 | 7-Mar-79 | 2003 | 15.35 | 35,662 | 0.00 | 0.00 | 0.00 | | | |
| 750020 | 8-Mar-79 | 0201 | 1.55 | 35,664 | 0.00 | 0.00 | 0.00 | | | |
| 750021 | 9-Mar-79 | 0201 | 300.00 | 35,964 | 269.00 | 0.00 | 0.00 | | | |
| 901229 | 9-Mar-79 | 2003 | 23.01 | 35,987 | 7.51 | 0.00 | 0.00 | | | |
| 901230 | 12-Mar-79 | 2003 | 18.34 | 36,005 | 13.95 | 0.00 | 0.00 | | | |
| 901231 | 14-Mar-79 | 2003 | 60.00 | 36,065 | 56.07 | 0.00 | 0.00 | | | |
| 902148 | 14-Mar-79 | 2004 | 1.50 | 36,067 | 0.00 | 0.00 | 0.00 | | | |
| 750022 | 15-Mar-79 | 0201 | 300.00 | 36,367 | 249.00 | 0.00 | 0.00 | | | |
| 902149 | 16-Mar-79 | 2004 | 50.07 | 36,417 | 0.00 | 0.00 | 0.00 | | | |
| 750023 | 17-Mar-79 | 0201 | 300.00 | 36,717 | 275.62 | 0.00 | 0.00 | | | |
| 901232 | 17-Mar-79 | 2003 | 520.00 | 37,237 | 427.10 | 0.00 | 0.00 | | | |
| 750024 | 19-Mar-79 | 0201 | 300.00 | 37,537 | 295.56 | 0.00 | 0.00 | | | |
| 750025 | 21-Mar-79 | 0201 | 300.00 | 37,837 | 295.58 | 0.00 | 0.00 | | | |
| 750026 | 23-Mar-79 | 0201 | 289.41 | 38,126 | 284.97 | 0.00 | 0.00 | | | |
| 902150 | 24-Mar-79 | 2004 | 50.08 | 38,176 | 46.16 | 0.00 | 0.00 | | | |
| 902151 | 27-Mar-79 | 2004 | 520.00 | 38,696 | 424.66 | 0.00 | 0.00 | | | |
| 750027 | 29-Mar-79 | 0201 | 50.00 | 38,746 | 45.60 | 0.00 | 0.00 | | | |
| 750028 | 31-Mar-79 | 0201 | 300.00 | 39,046 | 295.55 | 0.00 | 0.00 | | | |
| 901233 | 31-Mar-79 | 0006 | 1.50 | 39,048 | 0.00 | 0.00 | 0.00 | | | |
| 902152 | 1-Apr-79 | 2004 | 520.00 | 39,568 | 424.66 | 0.00 | 0.00 | | | |
| 750029 | 2-Apr-79 | 0201 | 300.00 | 39,868 | 164.52 | 0.00 | 0.00 | | | |
| 902153 | 3-Apr-79 | 2004 | 823.07 | 40,691 | 519.15 | 0.00 | 0.00 | | | |
| 750030 | 4-Apr-79 | 0201 | 50.00 | 40,741 | 45.56 | 0.00 | 0.00 | | | |
| 901234 | 5-Apr-79 | 0006 | 60.02 | 40,801 | 56.16 | 0.00 | 0.00 | | | |
| 750031 | 6-Apr-79 | 0201 | 300.00 | 41,101 | 295.44 | 0.00 | 0.00 | | | |
| 901235 | 8-Apr-79 | 0006 | 520.02 | 41,621 | 427.15 | 0.00 | 0.00 | | | |
| 750032 | 13-Apr-79 | 0201 | 350.21 | 41,971 | 195.90 | 0.00 | 0.00 | | | |
| 750033 | 16-Apr-79 | 0201 | 252.51 | 42,223 | 248.42 | 0.00 | 0.00 | | | |
| 750034 | 18-Apr-79 | 0201 | 350.00 | 42,573 | 195.88 | 0.00 | 0.00 | | | |
| 750035 | 19-Apr-79 | 0201 | 343.90 | 42,917 | 195.90 | 0.00 | 0.00 | | | |
| 902154 | 19-Apr-79 | 2005 | 1.54 | 42,919 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750036 | 21-Apr-79 | 0201 | 300.00 | 43,219 | 295.84 | 0.00 | 0.00 | | | |
| 902155 | 24-Apr-79 | 2005 | 80.07 | 43,299 | 62.70 | 0.00 | 0.00 | | | |
| 750037 | 25-Apr-79 | 0201 | 300.00 | 43,599 | 295.84 | 0.00 | 0.00 | | | |
| 901236 | 26-Apr-79 | 2007 | 1.50 | 43,600 | 0.00 | 0.00 | 0.00 | | | |
| 750038 | 27-Apr-79 | 0201 | 300.02 | 43,900 | 295.86 | 0.00 | 0.00 | | | |
| 750039 | 30-Apr-79 | 0201 | 350.00 | 44,250 | 195.80 | 0.00 | 0.00 | | | |
| 750040 | 2-May-79 | 0201 | 382.77 | 44,633 | 195.80 | 0.00 | 0.00 | | | |
| 901237 | 2-May-79 | 2007 | 100.05 | 44,733 | 96.17 | 0.00 | 0.00 | | | |
| SF05-01A | 4-May-79 | 2002 | 1.51 | 44,735 | 0.00 | 0.00 | 0.00 | | | |
| SF05-01B | 4-May-79 | 2003 | 1.52 | 44,736 | 0.00 | 0.00 | 0.00 | | | |
| SF05-01C | 4-May-79 | 0006 | 1.50 | 44,738 | 0.00 | 0.00 | 0.00 | | | |
| 901238 | 5-May-79 | 2007 | 61.87 | 44,800 | 29.10 | 0.00 | 0.00 | | | |
| 902156 | 7-May-79 | 2004 | 10.05 | 44,810 | 6.15 | 0.00 | 0.00 | | | |
| 901239 | 10-May-79 | 2007 | 285.30 | 45,095 | 252.42 | 0.00 | 0.00 | | | |
| 902157 | 10-May-79 | 2004 | 90.50 | 45,186 | 55.09 | 0.00 | 0.00 | | | |
| 901240 | 12-May-79 | 2007 | 520.06 | 45,706 | 427.13 | 0.00 | 0.00 | | | |
| 750041 | 14-May-79 | 0201 | 4.32 | 45,710 | 0.07 | 0.00 | 0.00 | | | |
| 902158 | 22-May-79 | 2004 | 27.67 | 45,738 | 23.77 | 0.00 | 0.00 | | | |
| 901241 | 23-May-79 | 2005 | 100.07 | 45,838 | 85.19 | 0.00 | 0.00 | | | |
| 901242 | 26-May-79 | 2005 | 520.04 | 46,358 | 427.14 | 0.00 | 0.00 | | | |
| 902159 | 31-May-79 | 2004 | 100.07 | 46,458 | 85.15 | 0.00 | 0.00 | | | |
| 902160 | 2-Jun-79 | 2004 | 520.00 | 46,978 | 424.60 | 0.00 | 0.00 | | | |
| 902161 | 8-Jun-79 | 2004 | 665.00 | 47,643 | 614.61 | 0.00 | 0.00 | | | |
| 901243 | 9-Jun-79 | 2006 | 1.50 | 47,644 | 0.00 | 0.00 | 0.00 | | | |
| 901244 | 12-Jun-79 | 2006 | 100.07 | 47,744 | 96.23 | 0.00 | 0.00 | | | |
| SF05A-1A | 12-Jun-79 | 2002 | 54.60 | 47,799 | 50.73 | 0.00 | 0.00 | | | |
| SF05A-1B | 12-Jun-79 | 2003 | 55.69 | 47,855 | 51.76 | 0.00 | 0.00 | | | |
| SF05A-1C | 12-Jun-79 | 0006 | 54.07 | 47,909 | 50.21 | 0.00 | 0.00 | | | |
| 902162 | 13-Jun-79 | 2004 | 4.45 | 47,913 | 0.58 | 0.00 | 0.00 | | | |
| 901245 | 16-Jun-79 | 2006 | 520.04 | 48,433 | 427.18 | 0.00 | 0.00 | | | |
| 902163 | 21-Jun-79 | 2004 | 520.06 | 48,953 | 424.61 | 0.00 | 0.00 | | | |
| 902164 | 25-Jun-79 | 2004 | 520.06 | 49,473 | 430.85 | 0.00 | 0.00 | | | |
| 902165 | 27-Jun-79 | 2004 | 823.06 | 50,296 | 519.18 | 0.00 | 0.00 | | | |
| SF06-01A | 2-Jul-79 | 2002 | 18.49 | 50,315 | 14.64 | 0.00 | 0.00 | X | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Considered by this Study: Catastrophic Failures | Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| SF06-01B | 2-Jul-79 | 2003 | 19.36 | 50,334 | 15.49 | 0.00 | 0.00 | | | |
| SF06-01C | 2-Jul-79 | 0006 | 19.96 | 50,354 | 16.12 | 0.00 | 0.00 | | | |
| 750042 | 6-Jul-79 | 0007 | 0.00 | 50,354 | 0.00 | 0.00 | 0.00 | | | |
| 750043 | 9-Jul-79 | 0007 | 0.00 | 50,354 | 0.00 | 0.00 | 0.00 | | | |
| 750044 | 10-Jul-79 | 0007 | 1.30 | 50,355 | 0.00 | 0.00 | 0.00 | | | |
| 750045 | 12-Jul-79 | 0007 | 1.56 | 50,357 | 0.00 | 0.00 | 0.00 | | | |
| 901246 | 12-Jul-79 | 2007 | 3.73 | 50,361 | 0.00 | 0.00 | 0.00 | | | |
| 901247 | 16-Jul-79 | 2007 | 100.05 | 50,461 | 96.23 | 0.00 | 0.00 | | | |
| 902166 | 20-Jul-79 | 2004 | 1.54 | 50,462 | 0.00 | 0.00 | 0.00 | | | |
| 902167 | 24-Jul-79 | 2004 | 10.07 | 50,472 | 6.25 | 0.00 | 0.00 | | | |
| 902168 | 26-Jul-79 | 2004 | 50.04 | 50,522 | 34.68 | 0.00 | 0.00 | | | |
| 902169 | 31-Jul-79 | 2004 | 100.07 | 50,623 | 56.68 | 0.00 | 0.00 | | | |
| 901248 | 3-Aug-79 | 0007 | 1.57 | 50,624 | 0.00 | 0.00 | 0.00 | | | |
| 901249 | 4-Aug-79 | 0007 | 50.05 | 50,674 | 46.24 | 0.00 | 0.00 | | | |
| 901250 | 11-Aug-79 | 0007 | 6.48 | 50,681 | 2.65 | 0.00 | 0.00 | | | |
| 902170 | 11-Aug-79 | 2004 | 1.51 | 50,682 | 0.00 | 0.00 | 0.00 | | | |
| 902171 | 13-Aug-79 | 2004 | 56.04 | 50,738 | 45.96 | 0.00 | 0.00 | | | |
| 901251 | 18-Aug-79 | 0007 | 10.05 | 50,748 | 6.23 | 0.00 | 0.00 | | | |
| 901252 | 21-Aug-79 | 0007 | 10.00 | 50,758 | 6.16 | 0.00 | 0.00 | | | |
| 901253 | 22-Aug-79 | 0007 | 1.53 | 50,760 | 0.00 | 0.00 | 0.00 | | | |
| 901254 | 27-Aug-79 | 0007 | 100.05 | 50,860 | 96.23 | 0.00 | 0.00 | | | |
| 902172 | 6-Sep-79 | 2004 | 6.63 | 50,866 | 2.84 | 0.00 | 0.00 | | | |
| 902173 | 8-Sep-79 | 2004 | 1.82 | 50,868 | 0.00 | 0.00 | 0.00 | | | |
| 901255 | 15-Sep-79 | 0007 | 34.55 | 50,903 | 29.18 | 0.00 | 0.00 | | | |
| 901256 | 17-Sep-79 | 0007 | 100.00 | 51,003 | 64.71 | 0.00 | 0.00 | | | |
| 902174 | 17-Sep-79 | 2004 | 135.96 | 51,139 | 100.66 | 0.00 | 0.00 | | | |
| 750046 | 19-Sep-79 | 0105 | 1.50 | 51,140 | 0.00 | 0.00 | 0.00 | | | |
| 902175 | 20-Sep-79 | 2004 | 257.48 | 51,398 | 222.17 | 0.00 | 0.00 | | | |
| 750047 | 22-Sep-79 | 0105 | 10.43 | 51,408 | 6.00 | 0.00 | 0.00 | | | |
| 902176 | 22-Sep-79 | 2004 | 520.06 | 51,928 | 424.68 | 0.00 | 0.00 | | | |
| 750048 | 25-Sep-79 | 0105 | 49.97 | 51,978 | 30.93 | 0.00 | 0.00 | | | |
| 750049 | 29-Sep-79 | 0105 | 5.16 | 51,983 | 1.53 | 0.00 | 0.00 | | | |
| 750050 | 1-Oct-79 | 0105 | 93.23 | 52,077 | 89.21 | 0.00 | 0.00 | | | |
| 902177 | 1-Oct-79 | 2004 | 520.06 | 52,597 | 424.62 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750051 | 6-Oct-79 | 0105 | 300.01 | 52,897 | 295.97 | 0.00 | 0:00 | | | |
| 901257 | 6-Oct-79 | 0008 | 1.50 | 52,898 | 0.00 | 0.00 | 0.00 | | | |
| 901258 | 10-Oct-79 | 0008 | 1.57 | 52,900 | 0.00 | 0.00 | 0.00 | | | |
| 902178 | 10-Oct-79 | 2004 | 10.00 | 52,910 | 6.12 | 0.00 | 0.00 | | | |
| 901259 | 11-Oct-79 | 0008 | 100.00 | 53,010 | 96.16 | 0.00 | 0.00 | | | |
| 902179 | 12-Oct-79 | 2004 | 823.00 | 53,833 | 519.13 | 0.00 | 0.00 | | | |
| 750052 | 16-Oct-79 | 0105 | 96.13 | 53,929 | 92.24 | 0.00 | 0.00 | | | |
| 901260 | 18-Oct-79 | 0008 | 520.00 | 54,449 | 424.68 | 0.00 | 0.00 | | | |
| 902180 | 20-Oct-79 | 2004 | 10.00 | 54,459 | 6.09 | 0.00 | 0.00 | | | |
| 750053 | 23-Oct-79 | 0105 | 300.00 | 54,759 | 287.10 | 0.00 | 0.00 | | | |
| 750054 | 26-Oct-79 | 0105 | 60.00 | 54,819 | 19.11 | 0.00 | 0.00 | | | |
| 901261 | 26-Oct-79 | 0008 | 520.00 | 55,339 | 424.66 | 0.00 | 0.00 | | | |
| 902181 | 26-Oct-79 | 2004 | 665.02 | 56,004 | 314.64 | 0.00 | 0.00 | | | |
| 750055 | 1-Nov-79 | 0105 | 94.56 | 56,098 | 16.11 | 0.00 | 0.00 | | | |
| 750056 | 3-Nov-79 | 0105 | 1.50 | 56,100 | 0.00 | 0.00 | 0.00 | | | |
| SF06-03A | 4-Nov-79 | 2002 | 9.72 | 56,110 | 5.88 | 0.00 | 0.00 | | | |
| SF06-03B | 4-Nov-79 | 2003 | 10.35 | 56,120 | 6.45 | 0.00 | 0.00 | | | |
| SF06-03C | 4-Nov-79 | 0006 | 8.69 | 56,129 | 4.81 | 0.00 | 0.00 | | | |
| 901262 | 24-Nov-79 | 0008 | 100.05 | 56,229 | 86.18 | 0.00 | 0.00 | | | |
| 750057 | 15-Dec-79 | 0007 | 1.50 | 56,230 | 0.00 | 0.00 | 0.00 | | | |
| SF06-04A | 17-Dec-79 | 0008 | 553.70 | 56,784 | 336.16 | 0.00 | 0.00 | | | |
| SF06-04B | 17-Dec-79 | 2003 | 508.75 | 57,293 | 336.04 | 0.00 | 0.00 | | | |
| SF06-04C | 17-Dec-79 | 0006 | 553.97 | 57,847 | 336.15 | 0.00 | 0.00 | | | |
| 750058 | 19-Dec-79 | 0007 | 350.00 | 58,197 | 116.12 | 0.00 | 0.00 | | | |
| 750059 | 27-Dec-79 | 0007 | 313.25 | 58,510 | 116.13 | 0.00 | 0.00 | | | |
| 750060 | 29-Dec-79 | 0007 | 300.00 | 58,810 | 296.14 | 0.00 | 0.00 | | | |
| 902182 | 9-Jan-80 | 2004 | 520.04 | 59,330 | 424.50 | 0.00 | 0.00 | | | |
| 750061 | 11-Jan-80 | 0007 | 300.00 | 59,630 | 146.12 | 0.00 | 0.00 | | | |
| 750062 | 14-Jan-80 | 0007 | 300.00 | 59,930 | 286.12 | 0.00 | 0.00 | | | |
| 902183 | 14-Jan-80 | 2004 | 520.00 | 60,450 | 424.48 | 0.00 | 0.00 | | | |
| 902184 | 18-Jan-80 | 2004 | 520.00 | 60,970 | 424.42 | 0.00 | 0.00 | | | |
| 901263 | 22-Jan-80 | 0009 | 1.50 | 60,971 | 0.00 | 0.00 | 0.00 | | | |
| 901264 | 24-Jan-80 | 0009 | 1.50 | 60,973 | 0.00 | 0.00 | 0.00 | | | |
| 750063 | 25-Jan-80 | 0007 | 300.00 | 61,273 | 146.08 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901265 | 25-Jan-80 | 0009 | [illegible].50 | 61,274 | 0.00 | 0.00 | 0.00 | | | |
| 750064 | 31-Jan-80 | 0007 | 300.00 | 61,574 | 145.96 | 0.00 | 0.00 | | | |
| 901266 | 31-Jan-80 | 0009 | [illegible] | 61,576 | 0.00 | 0.00 | 0.00 | | | |
| SF07-01A | 1-Feb-80 | 0008 | [illegible] | 61,581 | 0.92 | 0.00 | 0.00 | | | |
| SF07-01B | 1-Feb-80 | 2003 | [illegible] | 61,586 | 1.50 | 0.00 | 0.00 | | | |
| SF07-01C | 1-Feb-80 | 0006 | 4.61 | 61,591 | 0.66 | 0.00 | 0.00 | | | |
| 901267 | 2-Feb-80 | 0009 | 39.62 | 61,630 | 35.78 | 0.00 | 0.00 | | | |
| 902185 | 5-Feb-80 | 2004 | 520.00 | 62,150 | 430.52 | 0.00 | 0.00 | | | |
| 902186 | 7-Feb-80 | 2004 | 10.00 | 62,160 | 6.02 | 0.00 | 0.00 | | | |
| 901268 | 8-Feb-80 | 0009 | 520.00 | 62,680 | 424.70 | 0.00 | 0.00 | | | |
| 750065 | 11-Feb-80 | 0007 | 1.50 | 62,682 | 0.00 | 0.00 | 0.00 | | | |
| 750066 | 12-Feb-80 | 0007 | 300.00 | 62,982 | 248.38 | 0.00 | 0.00 | | | |
| 901269 | 15-Feb-80 | 0009 | 2.85 | 62,985 | 0.00 | 0.00 | 0.00 | | | |
| 750067 | 22-Feb-80 | 0007 | 300.00 | 63,285 | 254.34 | 0.00 | 0.00 | | | |
| SF07-02A | 28-Feb-80 | 0008 | 554.30 | 63,839 | 329.32 | 0.00 | 0.00 | | | |
| SF07-02B | 28-Feb-80 | 2003 | 523.43 | 64,362 | 329.26 | 0.00 | 0.00 | | | |
| SF07-02C | 28-Feb-80 | 0006 | 554.82 | 64,917 | 329.29 | 0.00 | 0.00 | | | |
| 901270 | 29-Feb-80 | 0009 | 520.00 | 65,437 | 424.36 | 0.00 | 0.00 | | | |
| 750068 | 1-Mar-80 | 0007 | 300.00 | 65,737 | 248.29 | 0.00 | 0.00 | | | |
| 902187 | 4-Mar-80 | 2004 | 100.00 | 65,837 | 95.88 | 0.00 | 0.00 | | | |
| 901271 | 5-Mar-80 | 0009 | 823.08 | 66,660 | 518.88 | 0.00 | 0.00 | | | |
| 750069 | 7-Mar-80 | 0007 | 300.00 | 66,960 | 254.26 | 0.00 | 0.00 | | | |
| 902188 | 7-Mar-80 | 2004 | 110.04 | 67,070 | 63.87 | 25.00 | 0.00 | | | |
| 902189 | 13-Mar-80 | 2004 | 125.06 | 67,195 | 89.96 | 10.00 | 10.00 | | | |
| 750070 | 15-Mar-80 | 0007 | 300.04 | 67,495 | 248.29 | 0.00 | 0.00 | | | |
| 901272 | 15-Mar-80 | 0009 | 665.03 | 68,161 | 614.34 | 0.00 | 0.00 | | | |
| 750071 | 18-Mar-80 | 0007 | 300.00 | 68,461 | 254.26 | 0.00 | 0.00 | | | |
| SF08-01A | 20-Mar-80 | 0008 | 539.38 | 69,000 | 357.11 | 0.00 | 0.00 | | | |
| SF08-01B | 20-Mar-80 | 2003 | 539.48 | 69,539 | 344.11 | 0.00 | 0.00 | | | |
| SF08-01C | 20-Mar-80 | 0006 | 539.61 | 70,079 | 357.11 | 0.00 | 0.00 | | | |
| 901273 | 22-Mar-80 | 0009 | 519.90 | 70,599 | 424.34 | 0.00 | 0.00 | | | |
| 902190 | 24-Mar-80 | 2004 | 241.04 | 70,840 | 236.14 | 0.50 | 0.24 | | | |
| 750072 | 26-Mar-80 | 0007 | 300.00 | 71,140 | 34.78 | 0.00 | 0.00 | | | |
| 901274 | 28-Mar-80 | 0009 | 520.00 | 71,660 | 430.60 | 0.00 | 0.00 | | | |

## SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750073 | 29-Mar-80 | 0007 | 300.00 | 71,960 | 28.72 | 0.00 | 0.00 | | | |
| 902191 | 31-Mar-80 | 2004 | 610.00 | 72,570 | 232.10 | 5.50 | 360.10 | | | |
| 750074 | 5-Apr-80 | 0007 | 300.00 | 72,870 | 254.28 | 0.00 | 0.00 | | | |
| 901275 | 8-Apr-80 | 0009 | 520.00 | 73,390 | 424.32 | 0.00 | 0.00 | | | |
| 750075 | 11-Apr-80 | 0007 | 10.00 | 73,400 | 5.74 | 0.00 | 0.00 | | | |
| 901276 | 12-Apr-80 | 0009 | 520.00 | 73,920 | 424.36 | 0.00 | 0.00 | | | |
| 750076 | 14-Apr-80 | 0007 | 10.00 | 73,930 | 5.74 | 0.00 | 0.00 | | | |
| 902192 | 14-Apr-80 | 2004 | 610.00 | 74,540 | 232.13 | 5.50 | 360.10 | | | |
| SF09-01A | 16-Apr-80 | 0008 | 5.84 | 74,546 | 1.64 | 0.00 | 0.00 | | | |
| SF09-01B | 16-Apr-80 | 2003 | 4.72 | 74,550 | 0.49 | 0.00 | 0.00 | | | |
| SF09-01C | 16-Apr-80 | 0006 | 6.62 | 74,557 | 2.46 | 0.00 | 0.00 | | | |
| 901277 | 18-Apr-80 | 0009 | 10.00 | 74,567 | 5.88 | 0.00 | 0.00 | | | |
| 902193 | 19-Apr-80 | 2004 | 610.00 | 75,177 | 232.18 | 5.50 | 360.10 | | | |
| 750077 | 21-Apr-80 | 0007 | 300.00 | 75,477 | 254.30 | 0.00 | 0.00 | | | |
| 901278 | 21-Apr-80 | 0009 | 10.00 | 75,487 | 5.87 | 0.00 | 0.00 | | | |
| 901279 | 24-Apr-80 | 0009 | 300.00 | 75,787 | 245.76 | 0.00 | 0.00 | | | |
| 901280 | 28-Apr-80 | 0009 | 520.00 | 76,307 | 424.32 | 0.00 | 0.00 | | | |
| 750078 | 30-Apr-80 | 0007 | 300.00 | 76,607 | 248.02 | 0.00 | 0.00 | | | |
| 750079 | 7-May-80 | 0007 | 300.00 | 76,907 | 248.33 | 0.00 | 0.00 | | | |
| 750080 | 15-May-80 | 0007 | 300.00 | 77,207 | 254.88 | 0.00 | 0.00 | | | |
| 750081 | 21-May-80 | 0007 | 300.00 | 77,507 | 285.83 | 0.00 | 0.00 | | | |
| SF09-02A | 30-May-80 | 0008 | 578.24 | 78,085 | 351.34 | 0.00 | 0.00 | | | |
| SF09-02B | 30-May-80 | 2003 | 548.81 | 78,634 | 351.14 | 0.00 | 0.00 | | | |
| SF09-02C | 30-May-80 | 0006 | 533.89 | 79,168 | 351.38 | 0.00 | 0.00 | | | |
| 902194 | 2-Jun-80 | 2005 | 520.00 | 79,688 | 427.14 | 0.00 | 0.00 | | | |
| 750082 | 5-Jun-80 | 0007 | 300.00 | 79,988 | 152.84 | 0.00 | 0.00 | | | |
| 901281 | 5-Jun-80 | 2006 | 520.00 | 80,508 | 424.30 | 0.00 | 0.00 | | | |
| 750083 | 9-Jun-80 | 0007 | 300.00 | 80,808 | 143.30 | 0.00 | 0.00 | | | |
| 750084 | 11-Jun-80 | 0007 | 300.00 | 81,108 | 145.88 | 0.00 | 0.00 | | | |
| 901282 | 16-Jun-80 | 2007 | 520.00 | 81,628 | 424.34 | 0.00 | 0.00 | | | |
| 750085 | 19-Jun-80 | 0007 | 300.00 | 81,928 | 227.50 | 0.00 | 0.00 | | | |
| 902195 | 20-Jun-80 | 2004 | 251.03 | 82,179 | 246.95 | 0.00 | 0.00 | | | |
| 750086 | 23-Jun-80 | 0007 | 300.00 | 82,479 | 254.12 | 0.00 | 0.00 | | | |
| 902196 | 24-Jun-80 | 2004 | 520.00 | 82,999 | 430.62 | 0.00 | 0.00 | | | |

## SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Considered by this Study: Catastrophic Failures | Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902197 | 2-Jul-80 | 2004 | 520.00 | 83,519 | 430.60 | 0.00 | 0.00 | | | |
| 750087 | 3-Jul-80 | 0007 | 300.00 | 83,819 | 246.75 | 0.00 | 0.00 | | | |
| SF10-01A | 12-Jul-80 | 0008 | 105.29 | 83,924 | 69.49 | 0.00 | 0.00 | | | |
| SF10-01B | 12-Jul-80 | 2003 | 105.92 | 84,030 | 70.00 | 0.00 | 0.00 | | | |
| SF10-01C | 12-Jul-80 | 0006 | 106.52 | 84,137 | 70.76 | 0.00 | 0.00 | X | X | X |
| 750088 | 15-Jul-80 | 0007 | 300.00 | 84,437 | 241.80 | 0.00 | 0.00 | | | |
| 902198 | 23-Jul-80 | 2004 | 8.53 | 84,445 | 4.53 | 0.00 | 0.00 | | X | |
| 750089 | 28-Jul-80 | 0007 | 130.00 | 84,575 | 95.82 | 0.00 | 0.00 | | | |
| 901283 | 28-Jul-80 | 0010 | 1.50 | 84,577 | 0.00 | 0.00 | 0.00 | | | |
| 901284 | 30-Jul-80 | 0010 | 9.89 | 84,587 | 0.00 | 0.00 | 0.00 | | X | |
| 750090 | 16-Aug-80 | 0007 | 160.00 | 84,747 | 145.76 | 0.00 | 0.00 | | | |
| 750091 | 20-Aug-80 | 0007 | 100.00 | 84,847 | 85.78 | 0.00 | 0.00 | | | |
| 901285 | 27-Aug-80 | 0009 | 1.56 | 84,848 | 0.00 | 0.00 | 0.00 | | | |
| 901286 | 29-Aug-80 | 0009 | 10.00 | 84,858 | 5.80 | 0.00 | 0.00 | | | |
| 901287 | 2-Sep-80 | 0009 | 100.00 | 84,958 | 95.76 | 0.00 | 0.00 | | | |
| 750092 | 3-Sep-80 | 0007 | 174.84 | 85,133 | 160.80 | 0.00 | 0.00 | | | |
| 902199 | 8-Sep-80 | 2008 | 1.50 | 85,135 | 0.00 | 0.00 | 0.00 | | | |
| 750093 | 9-Sep-80 | 0007 | 300.00 | 85,435 | 285.80 | 0.00 | 0.00 | | | |
| 901288 | 11-Sep-80 | 0009 | 392.60 | 85,827 | 356.90 | 0.00 | 0.00 | | | |
| 902200 | 13-Sep-80 | 2008 | 100.00 | 85,927 | 95.72 | 0.00 | 0.00 | | | |
| 902201 | 16-Sep-80 | 2008 | 250.00 | 86,177 | 218.50 | 9.70 | 0.00 | | | |
| 901289 | 18-Sep-80 | 0009 | 520.00 | 86,697 | 430.30 | 0.00 | 0.00 | | | |
| 750094 | 20-Sep-80 | 0007 | 285.27 | 86,982 | 281.21 | 0.00 | 0.00 | | | |
| 902202 | 23-Sep-80 | 2008 | 50.00 | 87,032 | 45.72 | 0.00 | 0.00 | | | |
| 750095 | 27-Sep-80 | 0007 | 99.52 | 87,132 | 85.80 | 0.00 | 0.00 | | | |
| 750096 | 30-Sep-80 | 0007 | 99.52 | 87,232 | 85.80 | 0.00 | 0.00 | | | |
| 750097 | 2-Oct-80 | 0007 | 100.12 | 87,332 | 85.80 | 0.00 | 0.00 | | | |
| 750098 | 4-Oct-80 | 0007 | 100.12 | 87,432 | 85.78 | 0.00 | 0.00 | | | |
| 750099 | 7-Oct-80 | 0007 | 137.06 | 87,569 | 85.84 | 0.00 | 0.00 | | | |
| 901290 | 7-Oct-80 | 0009 | 520.00 | 88,089 | 430.40 | 0.00 | 0.00 | | | |
| 750100 | 9-Oct-80 | 0007 | 100.01 | 88,189 | 85.79 | 0.00 | 0.00 | | | |
| 901291 | 10-Oct-80 | 0009 | 520.00 | 88,709 | 13.40 | 423.20 | 0.00 | | | |
| 750101 | 11-Oct-80 | 0007 | 100.01 | 88,809 | 14.81 | 0.00 | 0.00 | | | |
| 902203 | 11-Oct-80 | 0006 | 1.50 | 88,810 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902204 | 13-Oct-80 | 0006 | 260.00 | 89,070 | 231.80 | 0.00 | 0.00 | | | |
| 901292 | 15-Oct-80 | 0009 | 520.00 | 89,590 | 430.40 | 0.00 | 0.00 | | | |
| 750102 | 20-Oct-80 | 0007 | 300.00 | 89,890 | 248.30 | 0.00 | 0.00 | | | |
| 901293 | 22-Oct-80 | 0009 | 823.00 | 90,713 | 518.89 | 0.00 | 0.00 | | | |
| 901294 | 24-Oct-80 | 0009 | 665.00 | 91,378 | 610.40 | 0.00 | 0.00 | | | |
| 902205 | 28-Oct-80 | 2008 | 1.50 | 91,380 | 0.00 | 0.00 | 0.00 | | | |
| 902206 | 29-Oct-80 | 2008 | 100.00 | 91,480 | 95.76 | 0.00 | 0.00 | | | |
| 750103 | 3-Nov-80 | 0007 | 33.48 | 91,513 | 5.75 | 0.00 | 0.00 | | | |
| SF11-01A | 3-Nov-80 | 0008 | 20.70 | 91,534 | 16.61 | 0.00 | 0.00 | | | |
| SF11-01B | 3-Nov-80 | 2003 | 19.50 | 91,554 | 15.22 | 0.00 | 0.00 | | | |
| SF11-01C | 3-Nov-80 | 0006 | 21.44 | 91,575 | 17.36 | 0.00 | 0.00 | | | |
| 902207 | 4-Nov-80 | 2008 | 520.00 | 92,095 | 430.34 | 0.00 | 0.00 | | | |
| 750104 | 6-Nov-80 | 0007 | 10.00 | 92,105 | 5.71 | 0.00 | 0.00 | | | |
| 901295 | 6-Nov-80 | 0009 | 520.00 | 92,625 | 430.38 | 0.00 | 0.00 | | | |
| 750105 | 8-Nov-80 | 0007 | 10.00 | 92,635 | 5.82 | 0.00 | 0.00 | | | |
| 902208 | 10-Nov-80 | 2008 | 520.00 | 93,155 | 430.22 | 0.00 | 0.00 | | | |
| 750106 | 11-Nov-80 | 0007 | 15.00 | 93,170 | 5.96 | 0.00 | 0.00 | | | |
| 901296 | 11-Nov-80 | 0009 | 519.93 | 93,690 | 430.40 | 0.00 | 0.00 | | | |
| 750107 | 13-Nov-80 | 0007 | 3.64 | 93,694 | 0.00 | 0.00 | 0.00 | | | |
| 901297 | 13-Nov-80 | 0009 | 10.00 | 93,704 | 5.76 | 0.00 | 0.00 | | | |
| 750108 | 15-Nov-80 | 0007 | 15.00 | 93,719 | 5.98 | 0.00 | 0.00 | | | |
| 902209 | 15-Nov-80 | 2008 | 823.00 | 94,542 | 518.72 | 0.00 | 0.00 | | | |
| 750109 | 18-Nov-80 | 0007 | 15.00 | 94,557 | 5.72 | 0.00 | 0.00 | | | |
| 901298 | 19-Nov-80 | 0009 | 10.00 | 94,567 | 5.72 | 0.00 | 0.00 | | | |
| 902210 | 21-Nov-80 | 2008 | 665.00 | 95,232 | 610.46 | 0.00 | 0.00 | | | |
| 901299 | 24-Nov-80 | 0009 | 10.00 | 95,242 | 5.74 | 0.00 | 0.00 | | | |
| 750110 | 25-Nov-80 | 0007 | 450.00 | 95,692 | 10.76 | 0.00 | 0.00 | | | |
| 750111 | 1-Dec-80 | 0007 | 300.00 | 95,992 | 222.84 | 0.00 | 0.00 | | | |
| 901300 | 2-Dec-80 | 0009 | 10.00 | 96,002 | 5.82 | 0.00 | 0.00 | | | |
| SF11-02A | 4-Dec-80 | 0008 | 590.03 | 96,592 | 352.32 | 0.00 | 0.00 | | | |
| SF11-02B | 4-Dec-80 | 2003 | 441.76 | 97,033 | 352.08 | 0.00 | 0.00 | | | |
| SF11-02C | 4-Dec-80 | 0006 | 590.33 | 97,624 | 352.34 | 0.00 | 0.00 | | | |
| 902211 | 5-Dec-80 | 2008 | 250.00 | 97,874 | 245.80 | 0.00 | 0.00 | | | |
| 750112 | 6-Dec-80 | 0007 | 300.00 | 98,174 | 295.76 | 0.00 | 0.00 | | | |

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902212 | 10-Dec-80 | 2008 | 520.00 | 98,694 | 13.82 | 422.80 | 0.00 | | | |
| 901301 | 15-Dec-80 | 0009 | 823.00 | 99,517 | 518.78 | 0.00 | 0.00 | | | |
| 750113 | 16-Dec-80 | 0007 | 300.00 | 99,817 | 295.80 | 0.00 | 0.00 | | | |
| 750114 | 18-Dec-80 | 0007 | 300.00 | 100,117 | 295.80 | 0.00 | 0.00 | | | |
| 902213 | 18-Dec-80 | 2008 | 520.00 | 100,637 | 430.42 | 0.00 | 0.00 | | | |
| 750115 | 20-Dec-80 | 0007 | 300.00 | 100,937 | 295.79 | 0.00 | 0.00 | | | |
| 902214 | 23-Dec-80 | 2008 | 520.00 | 101,457 | 430.40 | 0.00 | 0.00 | | | |
| 902215 | 30-Dec-80 | 2008 | 520.00 | 101,977 | 430.20 | 0.00 | 0.00 | | | |
| 750116 | 2-Jan-81 | 0007 | 300.00 | 102,277 | 295.76 | 0.00 | 0.00 | | | |
| 902216 | 5-Jan-81 | 2008 | 520.00 | 102,797 | 430.20 | 0.00 | 0.00 | | | |
| 750117 | 9-Jan-81 | 0007 | 300.00 | 103,097 | 290.71 | 0.00 | 0.00 | | | |
| 901302 | 12-Jan-81 | 0009 | 1.50 | 103,098 | 0.00 | 0.00 | 0.00 | | | |
| SF12-01A | 17-Jan-81 | 0008 | 628.36 | 103,727 | 624.11 | 0.00 | 0.00 | | | |
| SF12-01B | 17-Jan-81 | 2003 | 628.46 | 104,355 | 623.90 | 0.00 | 0.00 | | | |
| SF12-01C | 17-Jan-81 | 0006 | 238.94 | 104,594 | 234.76 | 0.00 | 0.00 | | | |
| 901303 | 19-Jan-81 | 0009 | 53.10 | 104,647 | 5.74 | 0.00 | 0.00 | | | |
| 901304 | 21-Jan-81 | 0009 | 81.70 | 104,729 | 5.74 | 0.00 | 0.00 | | | |
| 750118 | 22-Jan-81 | 0007 | 300.00 | 105,029 | 295.72 | 0.00 | 0.00 | | | |
| 901305 | 23-Jan-81 | 0009 | 79.57 | 105,108 | 5.75 | 0.00 | 0.00 | | | |
| 901306 | 26-Jan-81 | 0009 | 80.29 | 105,189 | 5.79 | 0.00 | 0.00 | | | |
| 750119 | 28-Jan-81 | 0007 | 5.25 | 105,194 | 0.85 | 0.00 | 0.00 | | | |
| 901307 | 28-Jan-81 | 0009 | 75.02 | 105,269 | 5.77 | 0.00 | 0.00 | | X | |
| 902217 | 31-Jan-81 | 2009 | 1.57 | 105,270 | 0.00 | 0.00 | 0.00 | | | |
| 750120 | 2-Feb-81 | 0007 | 235.00 | 105,505 | 230.68 | 0.00 | 0.00 | | | |
| 902218 | 3-Feb-81 | 2009 | 100.00 | 105,605 | 95.94 | 0.00 | 0.00 | | | |
| 750121 | 9-Feb-81 | 0007 | 20.00 | 105,625 | 5.68 | 0.00 | 0.00 | | | |
| 902219 | 9-Feb-81 | 2009 | 520.00 | 106,145 | 418.38 | 0.00 | 0.00 | | | |
| FRF001-A | 20-Feb-81 | 2007 | 21.86 | 106,167 | 15.26 | 0.00 | 0.00 | | | |
| FRF001-B | 20-Feb-81 | 2006 | 23.83 | 106,191 | 17.13 | 0.00 | 0.00 | | | |
| FRF001-C | 20-Feb-81 | 2005 | 23.97 | 106,215 | 17.24 | 0.00 | 0.00 | | | |
| 750122 | 23-Feb-81 | 0110 | 1.50 | 106,217 | 0.00 | 0.00 | 0.00 | | | |
| 750123 | 25-Feb-81 | 0110 | 300.00 | 106,517 | 223.72 | 0.00 | 0.00 | | | |
| 901308 | 25-Feb-81 | 0006 | 3.90 | 106,520 | 0.00 | 0.00 | 0.00 | | | |
| 901309 | 28-Feb-81 | 0006 | 67.26 | 106,588 | 5.72 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750124 | 2-Mar-81 | 0110 | 99.96 | 106,688 | 58.18 | 0.00 | 0.00 | | | |
| 901310 | 3-Mar-81 | 0006 | 67.36 | 106,755 | 5.83 | 0.00 | 0.00 | | | |
| 901311 | 5-Mar-81 | 0006 | 64.30 | 106,819 | 5.80 | 0.00 | 0.00 | | | |
| 902220 | 6-Mar-81 | 0008 | 100.00 | 106,919 | 87.74 | 0.00 | 0.00 | | | |
| 902221 | 10-Mar-81 | 0008 | 610.00 | 107,529 | 236.39 | 361.00 | 0.00 | | | |
| 750125 | 11-Mar-81 | 0110 | 300.00 | 107,829 | 155.54 | 110.10 | 30.00 | | | |
| 902222 | 12-Mar-81 | 0008 | 610.00 | 108,439 | 236.36 | 361.00 | 0.00 | | | |
| 750126 | 14-Mar-81 | 0110 | 300.00 | 108,739 | 75.48 | 1.00 | 219.20 | | | |
| 901312 | 14-Mar-81 | 0006 | 60.11 | 108,799 | 5.80 | 0.00 | 0.00 | | | |
| 902223 | 17-Mar-81 | 0008 | 610.00 | 109,409 | 236.22 | 1.00 | 360.40 | | | |
| 901313 | 18-Mar-81 | 0006 | 63.66 | 109,473 | 5.88 | 0.00 | 0.00 | | | |
| 901314 | 20-Mar-81 | 0006 | 47.63 | 109,521 | 43.47 | 0.00 | 0.00 | | | |
| 902224 | 23-Mar-81 | 0008 | 610.00 | 110,131 | 236.26 | 1.00 | 360.40 | | | |
| 750127 | 24-Mar-81 | 0110 | 15.00 | 110,146 | 5.72 | 0.00 | 0.00 | | | |
| 750128 | 26-Mar-81 | 0110 | 10.00 | 110,156 | 5.68 | 0.00 | 0.00 | | | |
| 901315 | 26-Mar-81 | 0006 | 66.84 | 110,223 | 5.88 | 0.00 | 0.00 | | | |
| 750129 | 28-Mar-81 | 0110 | 15.00 | 110,238 | 5.56 | 0.00 | 0.00 | | | |
| 750130 | 31-Mar-81 | 0110 | 15.00 | 110,253 | 5.68 | 0.00 | 0.00 | | | |
| STS001-A | 12-Apr-81 | 2007 | 519.42 | 110,772 | 432.45 | 0.00 | 0.00 | | | |
| STS001-B | 12-Apr-81 | 2006 | 519.56 | 111,292 | 432.60 | 0.00 | 0.00 | | | |
| STS001-C | 12-Apr-81 | 2005 | 519.68 | 111,811 | 432.76 | 0.00 | 0.00 | | | |
| 750131 | 13-Apr-81 | 0110 | 118.14 | 111,929 | 55.65 | 57.84 | 0.00 | | | |
| 902225 | 13-Apr-81 | 0204 | 1.50 | 111,931 | 0.00 | 0.00 | 0.00 | | | |
| 901316 | 14-Apr-81 | 0006 | 15.00 | 111,946 | 5.84 | 0.00 | 0.00 | | | |
| 902226 | 15-Apr-81 | 0204 | 3.71 | 111,950 | 0.00 | 0.00 | 0.00 | | | |
| 750132 | 17-Apr-81 | 0110 | 300.00 | 112,250 | 42.16 | 1.00 | 190.20 | | | |
| 902227 | 17-Apr-81 | 0204 | 3.80 | 112,253 | 0.00 | 0.00 | 0.00 | | | |
| 901317 | 20-Apr-81 | 0006 | 15.00 | 112,268 | 5.86 | 0.00 | 0.00 | | | |
| 901318 | 21-Apr-81 | 0006 | 1.50 | 112,270 | 0.00 | 0.00 | 0.00 | | | |
| 902228 | 21-Apr-81 | 0204 | 100.00 | 112,370 | 95.48 | 0.00 | 0.00 | | | |
| 901319 | 23-Apr-81 | 0006 | 100.00 | 112,470 | 85.82 | 0.00 | 0.00 | | | |
| 902229 | 24-Apr-81 | 0204 | 100.00 | 112,570 | 95.39 | 0.00 | 0.00 | | | |
| 750133 | 27-Apr-81 | 0110 | 300.00 | 112,870 | 71.06 | 5.70 | 189.90 | | | |
| 902230 | 27-Apr-81 | 0204 | 270.00 | 113,140 | 5.94 | 1.00 | 239.20 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902231 | 5-May-81 | 0204 | 268.80 | 113,409 | 45.96 | 1.00 | 199:20 | | | |
| 750134 | 7-May-81 | 0110 | 300.00 | 113,709 | 5.92 | 1.50 | 261.10 | | | |
| 902232 | 7-May-81 | 0204 | 520.00 | 114,229 | 12.09 | 9.70 | 402.80 | | | |
| 750135 | 9-May-81 | 0110 | 300.00 | 114,529 | 6.20 | 1.50 | 260.90 | | | |
| 902233 | 9-May-81 | 0204 | 500.00 | 115,029 | 12.28 | 9.70 | 382.60 | | | |
| 901320 | 11-May-81 | 2108 | 1.48 | 115,030 | 0.00 | 0.00 | 0.00 | | | |
| 750136 | 12-May-81 | 0110 | 300.00 | 115,330 | 5.80 | 1.50 | 261.10 | | | |
| 901321 | 13-May-81 | 2108 | 300.00 | 115,630 | 295.62 | 0.00 | 0.00 | | | |
| 750137 | 14-May-81 | 0110 | 1.33 | 115,632 | 0.00 | 0.00 | 0.00 | | | |
| 902234 | 14-May-81 | 0204 | 500.00 | 116,132 | 32.02 | 29.70 | 222.80 | | | |
| 750138 | 19-May-81 | 0110 | 300.00 | 116,432 | 6.06 | 1.50 | 261.00 | | | |
| 902235 | 19-May-81 | 0204 | 500.00 | 116,932 | 45.82 | 42.00 | 127.00 | | | |
| 901322 | 23-May-81 | 2108 | 290.00 | 117,222 | 160.82 | 85.00 | 20.00 | | | |
| 902236 | 23-May-81 | 0204 | 500.00 | 117,722 | 45.97 | 42.00 | 127.00 | | | |
| 750139 | 26-May-81 | 0110 | 300.00 | 118,022 | 6.00 | 1.50 | 261.10 | | | |
| 901323 | 26-May-81 | 2108 | 260.00 | 118,282 | 165.94 | 60.50 | 20.00 | | | |
| 901324 | 28-May-81 | 2108 | 520.00 | 118,802 | 65.45 | 1.00 | 449.20 | | | |
| 901325 | 30-May-81 | 2108 | 520.00 | 119,322 | 65.34 | 1.00 | 449.20 | | | |
| 902237 | 5-Jun-81 | 0204 | 50.00 | 119,372 | 10.76 | 1.00 | 15.00 | | | |
| 901326 | 6-Jun-81 | 2108 | 300.00 | 119,672 | 295.56 | 0.00 | 0.00 | | | |
| 902238 | 9-Jun-81 | 0204 | 475.00 | 120,147 | 6.03 | 2.00 | 385.90 | | | |
| 901327 | 11-Jun-81 | 2108 | 520.00 | 120,667 | 65.42 | 1.00 | 449.20 | | | |
| 901328 | 16-Jun-81 | 2108 | 520.00 | 121,187 | 65.46 | 1.00 | 449.20 | | | |
| 902239 | 19-Jun-81 | 0204 | 25.00 | 121,212 | 6.20 | 1.00 | 5.20 | | | |
| 750140 | 20-Jun-81 | 0110 | 300.00 | 121,512 | 5.50 | 1.50 | 261.10 | | | |
| 902240 | 22-Jun-81 | 0204 | 10.00 | 121,522 | 5.72 | 0.00 | 0.00 | | | |
| 901329 | 23-Jun-81 | 2108 | 500.00 | 122,022 | 13.50 | 10.25 | 377.40 | | | |
| 902241 | 24-Jun-81 | 0204 | 15.00 | 122,037 | 5.96 | 0.50 | 4.20 | | | |
| 750141 | 27-Jun-81 | 0110 | 300.00 | 122,337 | 5.52 | 1.50 | 261.10 | | | |
| 750142 | 30-Jun-81 | 0110 | 300.00 | 122,637 | 5.49 | 1.50 | 261.10 | | | |
| 902242 | 2-Jul-81 | 0204 | 300.00 | 122,937 | 6.89 | 2.00 | 215.60 | | | |
| 902243 | 8-Jul-81 | 0204 | 100.00 | 123,037 | 53.98 | 16.50 | 8.00 | | | |
| 901330 | 10-Jul-81 | 2108 | 170.00 | 123,207 | 75.11 | 75.50 | 15.00 | | | |
| 902244 | 14-Jul-81 | 0204 | 450.00 | 123,657 | 15.76 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901331 | 15-Jul-81 | 2108 | 233.14 | 123,890 | 208.52 | 1.00 | 8.20 | | X | |
| 750143 | 6-Aug-81 | 0110 | 39.00 | 123,929 | 8.91 | 8.60 | 7.20 | | | |
| 901332 | 8-Aug-81 | 0008 | 1.50 | 123,930 | 0.00 | 0.00 | 0.00 | | | |
| 750144 | 10-Aug-81 | 0110 | 48.00 | 123,978 | 14.46 | 8.60 | 7.20 | | | |
| 901333 | 11-Aug-81 | 0008 | 81.83 | 124,060 | 5.59 | 0.00 | 0.00 | | | |
| 902245 | 12-Aug-81 | 0204 | 25.00 | 124,085 | 6.20 | 1.00 | 4.20 | | | |
| 750145 | 14-Aug-81 | 0110 | 48.01 | 124,133 | 14.41 | 8.60 | 7.20 | | | |
| 901334 | 14-Aug-81 | 0008 | 84.18 | 124,217 | 5.66 | 0.00 | 0.00 | | | |
| 901335 | 17-Aug-81 | 0008 | 57.73 | 124,275 | 53.42 | 0.00 | 0.00 | | | |
| 750146 | 18-Aug-81 | 0110 | 10.00 | 124,285 | 5.62 | 0.00 | 0.00 | | | |
| 901336 | 19-Aug-81 | 0008 | 54.45 | 124,339 | 50.15 | 0.00 | 0.00 | | | |
| 902246 | 22-Aug-81 | 0204 | 25.00 | 124,364 | 6.22 | 1.00 | 4.20 | | | |
| 750147 | 24-Aug-81 | 0110 | 39.00 | 124,403 | 8.20 | 8.60 | 7.20 | | | |
| 902247 | 31-Aug-81 | 0204 | 200.00 | 124,603 | 6.12 | 1.00 | 179.20 | | | |
| 750148 | 2-Sep-81 | 0110 | 16.00 | 124,619 | 0.90 | 3.50 | 7.20 | | | |
| 902248 | 14-Sep-81 | 0204 | 500.00 | 125,119 | 6.46 | 1.00 | 479.20 | | | |
| 902249 | 21-Sep-81 | 0204 | 450.57 | 125,570 | 6.13 | 0.50 | 439.77 | X | | |
| 901337 | 7-Oct-81 | 0107 | 1.50 | 125,571 | 0.00 | 0.00 | 0.00 | | | |
| 901338 | 9-Oct-81 | 0107 | 15.20 | 125,587 | 10.99 | 0.00 | 0.00 | | | |
| 901339 | 13-Oct-81 | 0107 | 300.00 | 125,887 | 276.35 | 1.00 | 9.20 | | | |
| 901340 | 15-Oct-81 | 0107 | 405.50 | 126,292 | 5.98 | 0.50 | 394.70 | | | |
| 901341 | 30-Oct-81 | 0107 | 100.00 | 126,392 | 46.30 | 1.00 | 39.20 | | | |
| 901342 | 5-Nov-81 | 0107 | 200.00 | 126,592 | 6.23 | 1.00 | 179.20 | | | |
| 750149 | 7-Nov-81 | 0110F | 1.50 | 126,594 | 0.00 | 0.00 | 0.00 | | | |
| 901343 | 8-Nov-81 | 0107 | 500.00 | 127,094 | 6.23 | 1.00 | 479.20 | | | |
| STS002-A | 12-Nov-81 | 2007 | 520.13 | 127,614 | 435.78 | 0.00 | 0.00 | | | |
| STS002-B | 12-Nov-81 | 2006 | 520.24 | 128,134 | 436.03 | 0.00 | 0.00 | | | |
| STS002-C | 12-Nov-81 | 2005 | 520.36 | 128,654 | 436.07 | 0.00 | 0.00 | | | |
| 901344 | 14-Nov-81 | 0107 | 500.00 | 129,154 | 6.04 | 1.00 | 479.20 | | | |
| 750150 | 17-Nov-81 | 0110F | 60.00 | 129,214 | 35.38 | 1.00 | 9.20 | | | |
| 901345 | 18-Nov-81 | 0107 | 270.00 | 129,484 | 5.96 | 1.00 | 249.20 | | | |
| 901346 | 19-Nov-81 | 0107 | 500.00 | 129,984 | 5.95 | 1.00 | 479.20 | | | |
| 901347 | 30-Nov-81 | 0107 | 95.40 | 130,080 | 90.70 | 0.00 | 0.00 | | | |
| 901348 | 2-Dec-81 | 0107 | 750.00 | 130,830 | 200.13 | 1.00 | 509.20 | | | |

## SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750151 | 4-Dec-81 | 0110F | 3.61 | 130,833 | 0.00 | 0.00 | 0.00 | | | |
| 901349 | 4-Dec-81 | 0107 | 463.58 | 131,297 | 5.45 | 0.50 | 452.78 | | | |
| 902250 | 5-Dec-81 | 2010 | 1.50 | 131,298 | 0.00 | 0.00 | 0.00 | | | |
| 750152 | 10-Dec-81 | 0110F | 80.50 | 131,379 | 21.40 | 1.00 | 10.20 | | | |
| 902251 | 11-Dec-81 | 2010 | 100.00 | 131,479 | 95.88 | 0.00 | 0.00 | | | |
| 750153 | 14-Dec-81 | 0110F | 60.00 | 131,539 | 15.38 | 1.00 | 9.20 | | | |
| 902252 | 14-Dec-81 | 2010 | 500.00 | 132,039 | 12.44 | 9.70 | 380.10 | | | |
| 901350 | 16-Dec-81 | 0107 | 300.00 | 132,339 | 264.52 | 0.00 | 0.00 | | | |
| 902253 | 18-Dec-81 | 2010 | 500.00 | 132,839 | 12.43 | 9.70 | 380.10 | | | |
| 902254 | 21-Dec-81 | 2010 | 250.00 | 133,089 | 5.20 | 0.50 | 240.10 | | | |
| 901351 | 28-Dec-81 | 0107 | 500.00 | 133,589 | 96.22 | 1.00 | 389.20 | | | |
| 750154 | 29-Dec-81 | 0110F | 65.00 | 133,654 | 21.05 | 10.60 | 9.20 | | | |
| 901352 | 30-Dec-81 | 0107 | 500.00 | 134,154 | 11.98 | 9.70 | 380.20 | | | |
| 750155 | 2-Jan-82 | 0110F | 65.00 | 134,219 | 21.00 | 10.60 | 9.20 | | | |
| 902255 | 2-Jan-82 | 2010 | 750.00 | 134,969 | 199.62 | 1.00 | 510.10 | | | |
| 902256 | 5-Jan-82 | 2010 | 500.00 | 135,469 | 12.14 | 9.70 | 380.10 | | | |
| 902257 | 7-Jan-82 | 2010 | 595.00 | 136,064 | 5.04 | 0.50 | 585.10 | | | |
| 750156 | 11-Jan-82 | 0110F | 65.00 | 136,129 | 20.96 | 10.60 | 9.20 | | | |
| 750157 | 13-Jan-82 | 0110F | 200.00 | 136,329 | 44.00 | 10.80 | 9.20 | | | |
| 901353 | 14-Jan-82 | 0107 | 424.09 | 136,753 | 5.18 | 0.50 | 414.19 | | | |
| 750158 | 15-Jan-82 | 0110F | 200.00 | 136,953 | 120.56 | 1.00 | 9.20 | | | |
| 902258 | 16-Jan-82 | 2010 | 10.00 | 136,963 | 5.62 | 0.00 | 0.00 | | | |
| 901354 | 18-Jan-82 | 0107 | 270.00 | 137,233 | 46.04 | 0.50 | 219.20 | | | |
| 902259 | 18-Jan-82 | 2010 | 60.00 | 137,293 | 5.08 | 0.50 | 50.10 | | | |
| 901355 | 20-Jan-82 | 0107 | 500.00 | 137,793 | 46.02 | 0.50 | 449.20 | | | |
| 901356 | 25-Jan-82 | 0107 | 37.16 | 137,830 | 25.94 | 0.50 | 6.36 | | | |
| 902260 | 27-Jan-82 | 2010 | 250.00 | 138,080 | 5.16 | 0.50 | 240.10 | | | |
| 902261 | 29-Jan-82 | 2010 | 500.00 | 138,580 | 12.26 | 9.70 | 380.20 | | | |
| 901357 | 1-Feb-82 | 0107 | 500.00 | 139,080 | 26.04 | 0.50 | 469.20 | | | |
| 902262 | 2-Feb-82 | 2010 | 500.00 | 139,580 | 12.66 | 382.14 | 0.00 | | | |
| 750159 | 4-Feb-82 | 0110F | 65.00 | 139,645 | 20.96 | 10.60 | 9.20 | | | |
| 902263 | 6-Feb-82 | 2010 | 500.00 | 140,145 | 12.14 | 9.70 | 384.08 | | | |
| 901358 | 8-Feb-82 | 0107 | 500.00 | 140,645 | 25.98 | 0.50 | 469.20 | | | |
| 902264 | 9-Feb-82 | 2010 | 10.00 | 140,655 | 5.74 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750160 | 12-Feb-82 | 0110F | 3.16 | 140,658 | 0.00 | 0.00 | 0.00 | X | X | X |
| 902265 | 19-Feb-82 | 2010 | 100.00 | 140,758 | 95.86 | 0.00 | 0.00 | | | |
| 902266 | 22-Feb-82 | 2010 | 500.00 | 141,258 | 12.38 | 9.70 | 380.10 | | | |
| 901359 | 7-Mar-82 | 2013 | 1.50 | 141,260 | 0.00 | 0.00 | 0.00 | | | |
| 902267 | 8-Mar-82 | 2010 | 500.00 | 141,760 | 12.40 | 9.70 | 380.10 | | | |
| 901360 | 10-Mar-82 | 2013 | 100.00 | 141,860 | 95.76 | 0.00 | 0.00 | | | |
| 750161 | 15-Mar-82 | 0107 | 100.00 | 141,960 | 83.88 | 1.00 | 9.20 | | | |
| 902268 | 15-Mar-82 | 2010 | 500.00 | 142,460 | 12.14 | 9.70 | 380.20 | | | |
| 750162 | 22-Mar-82 | 0107 | 133.80 | 142,594 | 129.12 | 0.00 | 0.00 | | | |
| 901361 | 22-Mar-82 | 2013 | 500.00 | 143,094 | 12.58 | 9.70 | 380.20 | | | |
| STS003-A | 22-Mar-82 | 2007 | 519.67 | 143,613 | 435.66 | 0.00 | 0.00 | | | |
| STS003-B | 22-Mar-82 | 2006 | 519.80 | 144,133 | 435.69 | 0.00 | 0.00 | | | |
| STS003-C | 22-Mar-82 | 2005 | 519.91 | 144,653 | 435.74 | 0.00 | 0.00 | | | |
| 902269 | 23-Mar-82 | 2010 | 500.00 | 145,153 | 11.96 | 9.70 | 384.08 | | | |
| 750163 | 25-Mar-82 | 0107 | 2.00 | 145,155 | 0.00 | 0.00 | 0.00 | | | |
| 901362 | 26-Mar-82 | 2013 | 500.00 | 145,655 | 12.58 | 9.70 | 380.20 | | | |
| 902270 | 29-Mar-82 | 2010 | 250.00 | 145,905 | 4.99 | 0.50 | 240.10 | | | |
| 901363 | 30-Mar-82 | 2013 | 250.00 | 146,155 | 5.12 | 0.50 | 240.10 | | | |
| 750164 | 1-Apr-82 | 0107 | 118.94 | 146,274 | 5.74 | 0.50 | 108.14 | | | |
| 901364 | 7-Apr-82 | 2013 | 392.16 | 146,666 | 6.01 | 1.50 | 352.36 | | | |
| 750165 | 21-Apr-82 | 0107 | 280.00 | 146,946 | 5.31 | 1.50 | 240.20 | | | |
| 750166 | 29-Apr-82 | 0107 | 300.00 | 147,246 | 5.68 | 1.50 | 260.20 | | | |
| 902271 | 30-Apr-82 | 2010 | 300.00 | 147,546 | 295.88 | 0.00 | 0.00 | | | |
| 750167 | 2-May-82 | 0107 | 269.92 | 147,816 | 5.60 | 1.50 | 230.12 | | | |
| 902272 | 5-May-82 | 2010 | 500.00 | 148,316 | 12.42 | 9.70 | 380.30 | | | |
| 902273 | 8-May-82 | 2010 | 500.00 | 148,816 | 12.42 | 9.70 | 380.30 | | | |
| 902274 | 11-May-82 | 2010 | 60.00 | 148,876 | 5.18 | 0.50 | 50.10 | | | |
| 902275 | 13-May-82 | 2010 | 750.01 | 149,626 | 199.68 | 1.00 | 510.10 | | | |
| 750168 | 15-May-82 | 0107 | 300.00 | 149,926 | 5.68 | 1.50 | 260.20 | | | |
| 901365 | 15-May-82 | 2014 | 1.50 | 149,928 | 0.00 | 0.00 | 0.00 | | | |
| 901366 | 19-May-82 | 2014 | 100.00 | 150,028 | 95.83 | 0.00 | 0.00 | | | |
| 901367 | 25-May-82 | 2014 | 500.00 | 150,528 | 12.44 | 9.70 | 380.20 | | | |
| 902276 | 29-May-82 | 2010 | 595.00 | 151,123 | 5.54 | 1.00 | 575.10 | | | |
| 901368 | 3-Jun-82 | 2014 | 60.00 | 151,183 | 5.49 | 1.00 | 40.10 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901369 | 5-Jun-82 | 2014 | 500.00 | 151,683 | 12.34 | 9.70 | 380.20 | | | |
| 902277 | 6-Jun-82 | 2010 | 250.00 | 151,933 | 5.54 | 1.00 | 225.10 | | | |
| 901370 | 7-Jun-82 | 2014 | 750.00 | 152,683 | 199.70 | 1.00 | 510.10 | | | |
| 901371 | 15-Jun-82 | 2014 | 250.00 | 152,933 | 5.52 | 1.00 | 230.10 | | | |
| 901372 | 17-Jun-82 | 2014 | 250.00 | 153,183 | 5.50 | 1.00 | 230.10 | | | |
| 902278 | 18-Jun-82 | 2010 | 1.50 | 153,184 | 0.00 | 0.00 | 0.00 | | | |
| 901373 | 20-Jun-82 | 2014 | 50.00 | 153,234 | 35.89 | 0.00 | 0.00 | | | |
| 902279 | 20-Jun-82 | 2010 | 50.00 | 153,284 | 5.50 | 1.00 | 30.10 | | | |
| STS004-A | 27-Jun-82 | 2007 | 519.03 | 153,803 | 443.06 | 0.00 | 0.00 | | | |
| STS004-B | 27-Jun-82 | 2006 | 519.13 | 154,322 | 443.18 | 0.00 | 0.00 | | | |
| STS004-C | 27-Jun-82 | 2005 | 519.31 | 154,842 | 443.04 | 0.00 | 0.00 | | | |
| 902280 | 28-Jun-82 | 2010 | 1.50 | 154,843 | 0.00 | 0.00 | 0.00 | | | |
| 902281 | 29-Jun-82 | 2010 | 1.50 | 154,845 | 0.00 | 0.00 | 0.00 | | | |
| 901374 | 30-Jun-82 | 2014 | 500.00 | 155,345 | 12.46 | 9.70 | 380.20 | | | |
| 902282 | 1-Jul-82 | 2010 | 1.50 | 155,346 | 0.00 | 0.00 | 0.00 | | | |
| 901375 | 3-Jul-82 | 2014 | 50.00 | 155,396 | 35.83 | 0.00 | 0.00 | | | |
| 902283 | 3-Jul-82 | 2010 | 50.00 | 155,446 | 5.50 | 1.00 | 30.10 | | | |
| 902284 | 9-Jul-82 | 2010 | 500.00 | 155,946 | 12.25 | 9.70 | 380.20 | | | |
| 901376 | 10-Jul-82 | 2014 | 5.12 | 155,951 | 0.00 | 0.00 | 0.00 | | | |
| 902285 | 13-Jul-82 | 2010 | 10.00 | 155,961 | 5.75 | 0.00 | 0.00 | | | |
| 901377 | 14-Jul-82 | 2014 | 300.00 | 156,261 | 295.89 | 0.00 | 0.00 | | | |
| 902286 | 19-Jul-82 | 2010 | 250.00 | 156,511 | 14.62 | 1.00 | 230.10 | | | |
| 902287 | 21-Jul-82 | 2010 | 500.00 | 157,011 | 5.12 | 490.60 | 0.00 | | | |
| 901378 | 23-Jul-82 | 2014 | 1.50 | 157,013 | 0.00 | 0.00 | 0.00 | | | |
| 901379 | 25-Jul-82 | 2014 | 50.00 | 157,063 | 5.48 | 1.00 | 30.10 | | | |
| 750169 | 27-Jul-82 | 2208 | 1.49 | 157,064 | 0.00 | 0.00 | 0.00 | | | |
| 901380 | 27-Jul-82 | 2014 | 500.00 | 157,564 | 12.42 | 9.70 | 380.20 | | | |
| 902288 | 27-Jul-82 | 2010 | 250.00 | 157,814 | 5.38 | 1.00 | 230.10 | | | |
| 750170 | 29-Jul-82 | 2208 | 50.00 | 157,864 | 35.78 | 0.00 | 0.00 | | | |
| 901381 | 30-Jul-82 | 2014 | 500.00 | 158,364 | 12.40 | 9.70 | 380.20 | | | |
| 902289 | 1-Aug-82 | 2010 | 250.00 | 158,614 | 5.10 | 1.00 | 230.10 | | | |
| 901382 | 2-Aug-82 | 2014 | 500.00 | 159,114 | 12.15 | 9.70 | 384.08 | | | |
| 750171 | 4-Aug-82 | 2208 | 299.89 | 159,414 | 15.52 | 1.00 | 270.10 | | | |
| 902290 | 4-Aug-82 | 2010 | 750.00 | 160,164 | 199.44 | 1.00 | 510.10 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750172 | 7-Aug-82 | 2208 | 300.00 | 160,464 | 15.47 | 1.00 | 270.10 | | | |
| 902291 | 7-Aug-82 | 2010 | 250.00 | 160,714 | 61.64 | 10.50 | 9.70 | | | |
| 902292 | 9-Aug-82 | 2010 | 146.02 | 160,860 | 4.96 | 0.50 | 136.12 | | | |
| 901383 | 15-Aug-82 | 2014 | 300.00 | 161,160 | 295.85 | 0.00 | 0.00 | | | |
| 750173 | 18-Aug-82 | 2208 | 41.76 | 161,202 | 5.16 | 0.50 | 31.86 | | | |
| 901384 | 24-Aug-82 | 2014 | 595.00 | 161,797 | 5.26 | 0.50 | 585.10 | | | |
| 750174 | 25-Aug-82 | 2208 | 300.00 | 162,097 | 5.54 | 1.00 | 270.10 | | | |
| 750175 | 27-Aug-82 | 2208 | 116.08 | 162,213 | 5.26 | 0.50 | 106.18 | | | |
| 901385 | 27-Aug-82 | 2014 | 250.00 | 162,463 | 5.22 | 0.50 | 240.10 | | | |
| 902293 | 2-Sep-82 | 2012 | 1.50 | 162,464 | 0.00 | 0.00 | 0.00 | | | |
| 902294 | 10-Sep-82 | 2012 | 120.00 | 162,584 | 96.49 | 9.70 | 0.00 | | | |
| 901386 | 13-Sep-82 | 2011 | 1.54 | 162,586 | 0.00 | 0.00 | 0.00 | | | |
| 901387 | 19-Sep-82 | 2011 | 1.50 | 162,587 | 0.00 | 0.00 | 0.00 | | | |
| 901388 | 21-Sep-82 | 2011 | 5.40 | 162,593 | 0.92 | 0.00 | 0.00 | | | |
| 902295 | 23-Sep-82 | 2015 | 1.50 | 162,594 | 0.00 | 0.00 | 0.00 | | | |
| 901389 | 25-Sep-82 | 2011 | 120.00 | 162,714 | 96.42 | 9.70 | 0.00 | | | |
| 902296 | 25-Sep-82 | 2015 | 120.00 | 162,834 | 96.32 | 9.70 | 0.00 | | | |
| 902297 | 30-Sep-82 | 2015 | 23.50 | 162,858 | 5.30 | 0.50 | 13.50 | | | |
| 901390 | 4-Oct-82 | 2011 | 175.06 | 163,033 | 146.48 | 10.60 | 9.60 | | | |
| 902298 | 6-Oct-82 | 2015 | 185.00 | 163,218 | 146.24 | 10.60 | 9.60 | | | |
| 901391 | 7-Oct-82 | 2011 | 500.00 | 163,718 | 12.90 | 380.20 | 0.00 | | | |
| 902299 | 8-Oct-82 | 2015 | 500.00 | 164,218 | 12.51 | 9.70 | 380.10 | | | |
| 901392 | 18-Oct-82 | 2012 | 1.50 | 164,219 | 0.00 | 0.00 | 0.00 | | | |
| 901393 | 21-Oct-82 | 2012 | 51.00 | 164,270 | 46.76 | 0.00 | 0.00 | | | |
| 902300 | 23-Oct-82 | 2016 | 1.50 | 164,272 | 0.00 | 0.00 | 0.00 | | | |
| 902301 | 25-Oct-82 | 2016 | 4.60 | 164,277 | 0.20 | 0.00 | 0.00 | | | |
| 901394 | 26-Oct-82 | 2012 | 210.00 | 164,487 | 126.26 | 60.60 | 9.60 | | | |
| 750176 | 29-Oct-82 | 2308 | 1.52 | 164,488 | 0.00 | 0.00 | 0.00 | | | |
| 901395 | 30-Oct-82 | 2012 | 500.00 | 164,988 | 12.22 | 9.70 | 380.20 | | | |
| 750177 | 2-Nov-82 | 2308 | 210.00 | 165,198 | 126.28 | 60.60 | 9.60 | | | |
| 750178 | 7-Nov-82 | 2308 | 300.00 | 165,498 | 46.26 | 170.60 | 69.60 | | | |
| STS005-A | 11-Nov-82 | 2007 | 517.04 | 166,015 | 439.02 | 0.00 | 0.00 | | | |
| STS005-B | 11-Nov-82 | 2006 | 517.21 | 166,532 | 439.06 | 0.00 | 0.00 | | | |
| STS005-C | 11-Nov-82 | 2005 | 517.29 | 167,050 | 439.06 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Considered by this Study: Catastrophic Failures | Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902302 | 15-Nov-82 | 2016 | 215.40 | 167,265 | 85.80 | 125.10 | 0.00 | | | |
| 750179 | 16-Nov-82 | 2308 | 300.00 | 167,565 | 5.99 | 2.00 | 250.20 | | | |
| 750180 | 20-Nov-82 | 2308 | 300.9[illegible] | 167,866 | 46.24 | 80.60 | 159.60 | | | |
| 750181 | 24-Nov-82 | 2308 | 160.00 | 168,026 | 35.36 | 100.10 | 20.10 | | | |
| 750182 | 1-Dec-82 | 2308 | 299.77 | 168,326 | 14.85 | 2.00 | 250.20 | | | |
| 901396 | 5-Dec-82 | 2014 | 1.50 | 168,327 | 0.00 | 0.00 | 0.00 | | | |
| 902303 | 5-Dec-82 | 2016 | 210.00 | 168,537 | 126.22 | 60.60 | 9.60 | | | |
| 901397 | 7-Dec-82 | 2014 | 100.00 | 168,637 | 85.80 | 0.00 | 0.00 | | | |
| 902304 | 7-Dec-82 | 2016 | 500.00 | 169,137 | 12.54 | 9.70 | 380.20 | | | |
| 750183 | 8-Dec-82 | 2308 | 299.95 | 169,437 | 86.08 | 124.60 | 85.05 | | | |
| 901398 | 14-Dec-82 | 2014 | 500.00 | 169,937 | 12.39 | 9.70 | 380.20 | | | |
| 750184 | 16-Dec-82 | 2308 | 300.00 | 170,237 | 5.52 | 1.50 | 260.20 | | | |
| 901399 | 18-Dec-82 | 2014 | 500.00 | 170,737 | 12.40 | 9.70 | 380.20 | | | |
| FRF002-A | 18-Dec-82 | 2011 | 21.80 | 170,759 | 17.68 | 0.00 | 0.00 | | | |
| FRF002-B | 18-Dec-82 | 2015 | 23.76 | 170,783 | 19.35 | 0.00 | 0.00 | | | |
| FRF002-C | 18-Dec-82 | 2012 | 23.88 | 170,807 | 19.51 | 0.00 | 0.00 | | | |
| 901400 | 23-Dec-82 | 2014 | 500.00 | 171,307 | 12.58 | 9.70 | 380.20 | | | |
| 901401 | 4-Jan-83 | 2014 | 500.00 | 171,807 | 12.31 | 9.70 | 380.20 | | | |
| 750185 | 5-Jan-83 | 2308 | 10.00 | 171,817 | 5.53 | 0.00 | 0.00 | | | |
| 901402 | 8-Jan-83 | 2014 | 250.00 | 172,067 | 5.55 | 1.00 | 230.10 | | | |
| 750186 | 10-Jan-83 | 2308 | 15.00 | 172,082 | 4.92 | 0.50 | 5.10 | | | |
| 902305 | 11-Jan-83 | 2017 | 1.50 | 172,083 | 0.00 | 0.00 | 0.00 | | | |
| 902306 | 13-Jan-83 | 2017 | 86.44 | 172,170 | 82.28 | 0.00 | 0.00 | | | |
| 750187 | 15-Jan-83 | 2308 | 15.00 | 172,185 | 4.88 | 0.50 | 5.10 | | | |
| 750188 | 19-Jan-83 | 2308 | 300.00 | 172,485 | 6.16 | 2.00 | 250.20 | | | |
| 901403 | 22-Jan-83 | 2014 | 50.00 | 172,535 | 35.88 | 0.00 | 0.00 | | | |
| FRF003-A | 25-Jan-83 | 2011 | 21.80 | 172,556 | 17.46 | 0.00 | 0.00 | | | |
| FRF003-B | 25-Jan-83 | 2015 | 23.80 | 172,580 | 19.40 | 0.00 | 0.00 | | | |
| FRF003-C | 25-Jan-83 | 2012 | 23.92 | 172,604 | 19.46 | 0.00 | 0.00 | | | |
| 750189 | 28-Jan-83 | 2308 | 3.65 | 172,608 | 0.00 | 0.00 | 0.00 | | | |
| 901404 | 28-Jan-83 | 2014 | 250.00 | 172,858 | 5.52 | 1.00 | 230.10 | | | |
| 750190 | 4-Feb-83 | 2308 | 250.00 | 173,108 | 65.49 | 140.60 | 9.60 | | | |
| 901405 | 4-Feb-83 | 2014 | 500.00 | 173,608 | 12.40 | 9.70 | 380.20 | | | |
| 750191 | 12-Feb-83 | 2308 | 250.00 | 173,858 | 6.08 | 2.00 | 208.30 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902307 | 15-Feb-83 | 2017 | 500.00 | 174,358 | 13.13 | 380.20 | 0.00 | | | |
| 901406 | 17-Feb-83 | 2014 | 60.00 | 174,418 | 6.13 | 40.10 | 0.00 | | | |
| 750192 | 2-Mar-83 | 2308 | 39.89 | 174,458 | 5.51 | 29.99 | 0.00 | | | |
| 901407 | 13-Mar-83 | 2014 | 500.00 | 174,958 | 12.99 | 380.20 | 0.00 | | | |
| 750193 | 23-Mar-83 | 2308 | 70.00 | 175,028 | 6.10 | 50.10 | 0.00 | | | |
| STS006-A | 4-Apr-83 | 2017 | 505.76 | 175,533 | 14.99 | 400.40 | 0.00 | | | |
| STS006-B | 4-Apr-83 | 2015 | 505.87 | 176,039 | 14.95 | 400.28 | 0.00 | | | |
| STS006-C | 4-Apr-83 | 2012 | 505.99 | 176,545 | 15.25 | 400.02 | 0.00 | | | |
| 901408 | 6-Apr-83 | 2014 | 520.64 | 177,066 | 6.28 | 510.10 | 0.00 | | | |
| 902308 | 8-Apr-83 | 2011 | 1.50 | 177,067 | 0.00 | 0.00 | 0.00 | | | |
| 750194 | 14-Apr-83 | 2308 | 16.84 | 177,084 | 5.66 | 6.94 | 0.00 | | | |
| 902309 | 14-Apr-83 | 2011 | 4.95 | 177,089 | 0.39 | 0.00 | 0.00 | | | |
| 902310 | 18-Apr-83 | 2011 | 190.00 | 177,279 | 96.53 | 79.70 | 0.00 | | | |
| 901409 | 20-Apr-83 | 2014 | 750.00 | 178,029 | 200.65 | 510.10 | 0.00 | | | |
| 750195 | 22-Apr-83 | 2308 | 300.00 | 178,329 | 12.85 | 240.20 | 0.00 | | | |
| 901410 | 23-Apr-83 | 2014 | 595.00 | 178,924 | 5.66 | 585.10 | 0.00 | | | |
| 902311 | 29-Apr-83 | 2011 | 500.00 | 179,424 | 13.08 | 380.20 | 0.00 | | | |
| 750196 | 2-May-83 | 2308 | 150.00 | 179,574 | 65.19 | 59.70 | 0.00 | | | |
| 750197 | 16-May-83 | 2308 | 320.00 | 179,894 | 13.05 | 240.20 | 0.00 | | | |
| 901411 | 18-May-83 | 2018 | 1.50 | 179,896 | 0.00 | 0.00 | 0.00 | | | |
| 901412 | 21-May-83 | 2018 | 5.22 | 179,901 | 0.82 | 0.00 | 0.00 | | | |
| 750198 | 23-May-83 | 2308 | 320.00 | 180,221 | 19.18 | 240.20 | 0.00 | | | |
| 901413 | 25-May-83 | 2018 | 190.00 | 180,411 | 96.46 | 79.70 | 0.00 | | | |
| 750199 | 28-May-83 | 2308 | 190.00 | 180,601 | 35.90 | 140.10 | 0.00 | | | |
| 902312 | 3-Jun-83 | 2019 | 1.56 | 180,602 | 0.00 | 0.00 | 0.00 | | | |
| 750200 | 4-Jun-83 | 2308 | 190.00 | 180,792 | 25.83 | 150.10 | 0.00 | | | |
| 901414 | 6-Jun-83 | 2018 | 500.00 | 181,292 | 13.06 | 380.20 | 0.00 | | | |
| 750201 | 9-Jun-83 | 2308 | 100.00 | 181,392 | 6.07 | 80.10 | 0.00 | | | |
| 902313 | 9-Jun-83 | 2019 | 190.00 | 181,582 | 96.47 | 79.70 | 0.00 | | | |
| STS007-A | 18-Jun-83 | 2017 | 506.50 | 182,089 | 13.98 | 402.10 | 0.00 | | | |
| STS007-B | 18-Jun-83 | 2015 | 506.60 | 182,596 | 13.89 | 402.10 | 0.00 | | | |
| STS007-C | 18-Jun-83 | 2012 | 506.71 | 183,102 | 14.09 | 401.95 | 0.00 | | | |
| 902314 | 20-Jun-83 | 2019 | 500.00 | 183,602 | 13.05 | 380.70 | 0.00 | | | |
| 750202 | 21-Jun-83 | 2308 | 2.20 | 183,604 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 750203 | 25-Jun-83 | 2308 | 100.00 | 183,704 | 6.06 | 80.10 | 0.00 | | | |
| 750204 | 30-Jun-83 | 2308 | 320.02 | 184,024 | 12.99 | 240.20 | 0.00 | | | |
| 750205 | 6-Jul-83 | 2308 | 320.00 | 184,344 | 12.98 | 240.20 | 0.00 | | | |
| 901415 | 7-Jul-83 | 2010 | 1.50 | 184,346 | 0.00 | 0.00 | 0.00 | | | |
| 750206 | 11-Jul-83 | 2308 | 320.00 | 184,666 | 28.66 | 224.80 | 0.00 | | | |
| 901416 | 11-Jul-83 | 2010 | 190.00 | 184,856 | 96.46 | 79.70 | 0.00 | | | |
| 901417 | 15-Jul-83 | 2010 | 510.00 | 185,366 | 18.80 | 390.00 | 0.00 | | | |
| 901418 | 20-Jul-83 | 2010 | 510.00 | 185,876 | 18.80 | 390.00 | 0.00 | | | |
| 750207 | 21-Jul-83 | 2308 | 100.10 | 185,976 | 20.90 | 74.70 | 0.00 | | | |
| 750208 | 2-Aug-83 | 2308 | 320.00 | 186,236 | 12.79 | 240.20 | 0.00 | | | |
| 750209 | 8-Aug-83 | 2308 | 320.00 | 186,616 | 13.36 | 240.00 | 0.00 | | | |
| 901419 | 13-Aug-83 | 2010 | 510.00 | 187,126 | 18.36 | 390.20 | 0.00 | | | |
| 750210 | 19-Aug-83 | 2308 | 15.00 | 187,141 | 5.52 | 0.00 | 0.00 | | | |
| 902315 | 22-Aug-83 | 2109 | 1.50 | 187,143 | 0.00 | 0.00 | 0.00 | | | |
| 750211 | 24-Aug-83 | 2308 | 300.00 | 187,443 | 58.94 | 145.70 | 59.20 | | | |
| 750212 | 30-Aug-83 | 2308 | 300.00 | 187,743 | 15.67 | 44.00 | 214.70 | | | |
| 901420 | 30-Aug-83 | 2010 | 750.00 | 188,493 | 200.34 | 510.10 | 0.00 | | | |
| STS008-A | 30-Aug-83 | 2017 | 527.98 | 189,021 | 433.12 | 0.00 | 0.00 | | | |
| STS008-B | 30-Aug-83 | 2015 | 528.11 | 189,549 | 432.98 | 0.00 | 0.00 | | | |
| STS008-C | 30-Aug-83 | 2012 | 528.19 | 190,077 | 432.78 | 0.00 | 0.00 | | | |
| 902316 | 31-Aug-83 | 2109 | 4.24 | 190,081 | 0.09 | 0.00 | 0.00 | | | |
| 750213 | 10-Sep-83 | 2308 | 320.00 | 190,401 | 12.62 | 240.20 | 0.00 | | | |
| 750214 | 22-Sep-83 | 2308 | 300.00 | 190,701 | 79.16 | 115.60 | 59.20 | | | |
| 901421 | 25-Sep-83 | 2010 | 148.49 | 190,850 | 5.54 | 138.59 | 0.00 | | | |
| 750215 | 27-Sep-83 | 2308 | 300.00 | 191,150 | 15.78 | 43.90 | 214.80 | | | |
| 901422 | 28-Sep-83 | 2010 | 50.00 | 191,200 | 45.64 | 0.00 | 0.00 | | | |
| 901423 | 1-Oct-83 | 2010 | 50.00 | 191,250 | 35.56 | 0.00 | 0.00 | | | |
| 750216 | 5-Oct-83 | 2308 | 70.00 | 191,320 | 15.80 | 40.10 | 0.00 | | | |
| 902317 | 9-Oct-83 | 2109 | 1.50 | 191,321 | 0.00 | 0.00 | 0.00 | | | |
| 750217 | 11-Oct-83 | 2308 | 300.00 | 191,621 | 285.45 | 0.00 | 0.00 | | | |
| 901424 | 13-Oct-83 | 2010 | 50.00 | 191,671 | 36.16 | 9.70 | 0.00 | | | |
| 902318 | 14-Oct-83 | 2109 | 190.00 | 191,861 | 96.47 | 79.70 | 0.00 | | | |
| 901425 | 17-Oct-83 | 2010 | 510.00 | 192,371 | 18.52 | 390.20 | 0.00 | | | |
| 750218 | 18-Oct-83 | 2308 | 300.00 | 192,671 | 15.60 | 270.10 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902319 | 18-Oct-83 | 2109 | 510.00 | 193,181 | 18.35 | 392.20 | 0.00 | | | |
| 750219 | 24-Oct-83 | 2308 | 300.00 | 193,481 | 15.67 | 270.10 | 0.00 | | | |
| 901426 | 24-Oct-83 | 2010 | 6.61 | 193,488 | 2.33 | 0.00 | 0.00 | | | |
| 750220 | 1-Nov-83 | 2308 | 15.00 | 193,503 | 5.64 | 0.00 | 0.00 | | | |
| 901427 | 2-Nov-83 | 2010 | 510.00 | 194,013 | 18.42 | 390.20 | 0.00 | | | |
| 902320 | 4-Nov-83 | 2020 | 1.50 | 194,014 | 0.00 | 0.00 | 0.00 | | | |
| 902321 | 9-Nov-83 | 2020 | 1.50 | 194,016 | 0.00 | 0.00 | 0.00 | | | |
| 750221 | 10-Nov-83 | 2308 | 320.00 | 194,336 | 12.85 | 240.20 | 0.00 | | | |
| 902322 | 11-Nov-83 | 2020 | 190.00 | 194,526 | 96.37 | 79.70 | 0.00 | | | |
| 750222 | 15-Nov-83 | 2308 | 320.00 | 194,846 | 12.80 | 240.20 | 0.00 | | | |
| 901428 | 18-Nov-83 | 2010 | 510.00 | 195,356 | 18.44 | 390.20 | 0.00 | | | |
| 902323 | 19-Nov-83 | 2020 | 510.00 | 195,866 | 18.15 | 383.90 | 0.00 | | | |
| 901429 | 23-Nov-83 | 2010 | 595.00 | 196,461 | 5.70 | 585.10 | 0.00 | | | |
| STS009-A | 28-Nov-83 | 2011 | 515.52 | 196,976 | 11.17 | 406.20 | 0.00 | | | |
| STS009-B | 28-Nov-83 | 2018 | 515.65 | 197,492 | 11.32 | 406.25 | 0.00 | | | |
| STS009-C | 28-Nov-83 | 2019 | 515.78 | 198,008 | 11.52 | 406.45 | 0.00 | | | |
| 902324 | 1-Dec-83 | 2021 | 1.50 | 198,009 | 0.00 | 0.00 | 0.00 | | | |
| 902325 | 5-Dec-83 | 2021 | 190.00 | 198,199 | 96.48 | 79.70 | 0.00 | | | |
| 750223 | 6-Dec 83 | 2308 | 1.80 | 198,201 | 0.00 | 0.00 | 0.00 | | | |
| 901430 | 7-Dec 83 | 2017 | 510.00 | 198,711 | 18.52 | 390.20 | 0.00 | | | |
| 750224 | 10-Dec-83 | 2308 | 50.00 | 198,761 | 20.24 | 0.00 | 0.00 | | | |
| 902326 | 10-Dec-83 | 2021 | 510.00 | 199,271 | 18.22 | 384.10 | 0.00 | | | |
| 750225 | 15-Dec-83 | 2308 | 300.00 | 199,571 | 78.45 | 171.90 | 3.00 | | | |
| 750226 | 22-Dec-83 | 2308 | 150.00 | 199,721 | 39.56 | 55.10 | 29.60 | | | |
| 750227 | 28-Dec-83 | 2308 | 300.00 | 200,021 | 15.44 | 135.10 | 123.60 | | | |
| 901431 | 29-Dec-83 | 0108 | 1.50 | 200,022 | 0.00 | 0.00 | 0.00 | | | |
| 901432 | 4-Jan-84 | 0108 | 190.00 | 200,212 | 96.55 | 79.70 | 0.00 | | | |
| 750228 | 9-Jan-84 | 2308 | 5.18 | 200,218 | 0.90 | 0.00 | 0.00 | | | |
| 902327 | 10-Jan-84 | 2010 | 6.42 | 200,224 | 2.30 | 0.00 | 0.00 | | | |
| 750229 | 13-Jan-84 | 2308 | 300.00 | 200,524 | 79.33 | 115.70 | 59.20 | | | |
| 902328 | 15-Jan-84 | 2010 | 510.00 | 201,034 | 18.40 | 384.10 | 0.00 | | | |
| 750230 | 19-Jan-84 | 2308 | 300.00 | 201,334 | 16.08 | 44.20 | 214.80 | | | |
| 901433 | 21-Jan-84 | 0108 | 700.00 | 202,034 | 5.67 | 301.50 | 379.60 | | | |
| 901434 | 24-Jan-84 | 0108 | 700.00 | 202,734 | 5.66 | 1.00 | 680.10 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Considered by this Study: Catastrophic Failures | Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902329 | 25-Jan-84 | 2010 | 510.00 | 203,244 | 18.54 | 384.00 | 0:00 | | | |
| 750231 | 30-Jan-84 | 2308 | 315.00 | 203,559 | 89.20 | 120.20 | 59.20 | | | |
| STS011-A | 3-Feb-84 | 2109 | 527.79 | 204,087 | 438.04 | 0.00 | 0.00 | | | |
| STS011-B | 3-Feb-84 | 2015 | 527.89 | 204,615 | 437.77 | 0.00 | 0.00 | | X | |
| STS011-C | 3-Feb-84 | 2012 | 528.01 | 205,143 | 437.27 | 0.00 | 0.00 | | | |
| 902330 | 4-Feb-84 | 2010 | 1.74 | 205,144 | 0.00 | 0.00 | 0.00 | | | |
| 750232 | 6-Feb-84 | 2308 | 300.00 | 205,444 | 15.40 | 64.10 | 194.60 | | | |
| 901435 | 8-Feb-84 | 0108 | 60.00 | 205,504 | 11.82 | 8.70 | 15.10 | | | |
| 902331 | 13-Feb-84 | 2010 | 510.00 | 206,014 | 18.48 | 390.20 | 0.00 | | | |
| 901436 | 14-Feb-84 | 0108 | 611.06 | 206,626 | 5.32 | 0.50 | 601.16 | X | | |
| 902332 | 13-Mar-84 | 2010 | 60.00 | 206,686 | 6.89 | 20.30 | 0.00 | | | |
| 902333 | 21-Mar-84 | 2010 | 60.00 | 206,746 | 6.14 | 8.70 | 0.00 | | | |
| 901437 | 22-Mar-84 | 2019 | 60.00 | 206,806 | 6.93 | 20.20 | 0.00 | | | |
| 901438 | 27-Mar-84 | 2019 | 510.00 | 207,316 | 18.47 | 390.20 | 0.00 | | | |
| 750233 | 6-Apr-84 | 2308 | 50.00 | 207,366 | 20.52 | 0.00 | 0.00 | | | |
| 901439 | 6-Apr-84 | 2019 | 250.00 | 207,616 | 35.71 | 190.10 | 0.00 | | | |
| STS013-A | 6-Apr-84 | 2109 | 517.14 | 208,133 | 13.44 | 410.34 | 0.00 | | | |
| STS013-B | 6-Apr-84 | 2020 | 517.25 | 208,650 | 13.60 | 410.05 | 0.00 | | | |
| STS013-C | 6-Apr-84 | 2012 | 517.40 | 209,167 | 14.36 | 409.31 | 0.00 | | | |
| 902334 | 7-Apr-84 | 2022 | 1.50 | 209,169 | 0.00 | 0.00 | 0.00 | | | |
| 901440 | 11-Apr-84 | 2019 | 250.00 | 209,419 | 35.66 | 190.10 | 0.00 | | | |
| 902335 | 12-Apr-84 | 2022 | 250.00 | 209,669 | 86.41 | 149.70 | 0.00 | | | |
| 750234 | 19-Apr-84 | 2308 | 100.00 | 209,769 | 16.60 | 15.50 | 30.10 | | | |
| 901441 | 2-May-84 | 0207 | 1.50 | 209,770 | 0.00 | 0.00 | 0.00 | | | |
| 901442 | 8-May-84 | 0207 | 100.00 | 209,870 | 76.59 | 9.70 | 0.00 | | | |
| 902336 | 10-May-84 | 2022 | 250.00 | 210,120 | 86.50 | 149.70 | 0.00 | | | |
| 901443 | 14-May-84 | 0207 | 110.00 | 210,230 | 76.56 | 14.20 | 6.00 | | | |
| 750235 | 19-May-84 | 2308 | 47.44 | 210,278 | 4.40 | 38.04 | 0.00 | | | |
| 901444 | 19-May-84 | 0207 | 160.00 | 210,438 | 96.65 | 15.60 | 14.60 | | | |
| 902337 | 22-May-84 | 2022 | 510.00 | 210,948 | 18.52 | 384.00 | 0.00 | | | |
| FRF004-A | 2-Jun-84 | 2021 | 17.60 | 210,965 | 13.30 | 0.00 | 0.00 | | | |
| FRF004-B | 2-Jun-84 | 2018 | 19.60 | 210,985 | 15.24 | 0.00 | 0.00 | | | |
| FRF004-C | 2-Jun-84 | 2017 | 19.72 | 211,005 | 15.44 | 0.00 | 0.00 | | | |
| 902338 | 8-Jun-84 | 2023 | 1.50 | 211,006 | 0.00 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901445 | 9-Jun-84 | 0207 | 100.00 | 211,106 | 17.24 | 15.50 | 30.10 | | | |
| 902339 | 13-Jun-84 | 2023 | 250.00 | 211,356 | 48.79 | 149.70 | 0.00 | | | |
| 750236 | 15-Jun-84 | 2308 | 100.00 | 211,456 | 14.60 | 15.50 | 30.10 | | | |
| 901446 | 15-Jun-84 | 0207 | 91.30 | 211,547 | 40.22 | 26.00 | 0.00 | | | |
| 750237 | 20-Jun-84 | 2308 | 300.00 | 211,847 | 78.80 | 115.70 | 59.20 | | | |
| 902340 | 21-Jun-84 | 2023 | 250.00 | 212,097 | 86.50 | 149.70 | 0.00 | | | |
| 750238 | 26-Jun-84 | 2308 | 300.00 | 212,397 | 16.20 | 53.10 | 205.60 | | | |
| STSA14-A | 26-Jun-84 | 2109 | 0.00 | 212,397 | 0.00 | 0.00 | 0.00 | | | |
| STSA14-B | 26-Jun-84 | 2018 | 2.00 | 212,399 | 0.00 | 0.00 | 0.00 | | | |
| STSA14-C | 26-Jun-84 | 2017 | 0.22 | 212,400 | 0.00 | 0.00 | 0.00 | | | |
| 901447 | 27-Jun-84 | 0207 | 100.00 | 212,500 | 17.26 | 15.50 | 30.10 | | | |
| 750239 | 30-Jun-84 | 2308 | 300.00 | 212,800 | 16.64 | 15.50 | 208.10 | | | |
| 902341 | 30-Jun-84 | 2023 | 510.00 | 213,310 | 18.47 | 390.20 | 0.00 | | | |
| 750240 | 9-Jul-84 | 2308 | 310.64 | 213,620 | 5.04 | 15.50 | 235.10 | | | |
| 901448 | 10-Jul-84 | 0207 | 500.00 | 214,120 | 18.08 | 16.50 | 380.10 | | | |
| 901449 | 14-Jul-84 | 0207 | 500.00 | 214,620 | 17.96 | 16.50 | 380.10 | | | |
| 750241 | 18-Jul-84 | 2308 | 100.00 | 214,720 | 16.97 | 15.50 | 30.10 | | | |
| 902342 | 19-Jul-84 | 2014 | 1.50 | 214,722 | 0.00 | 0.00 | 0.00 | | | |
| 902343 | 21-Jul-84 | 2014 | 250.00 | 214,972 | 48.82 | 149.70 | 0.00 | | | |
| 901450 | 26-Jul-84 | 0207 | 124.34 | 215,096 | 5.22 | 4.84 | 110.10 | | | |
| 750242 | 27-Jul-84 | 2308 | 100.00 | 215,196 | 16.95 | 15.50 | 30.10 | | | |
| 750243 | 7-Aug-84 | 2308 | 312.65 | 215,509 | 5.94 | 1.00 | 249.60 | | | |
| 902344 | 7-Aug-84 | 2014 | 250.00 | 215,759 | 48.87 | 149.70 | 0.00 | | | |
| 901451 | 9-Aug-84 | 0207 | 10.96 | 215,770 | 5.20 | 0.50 | 1.06 | | | |
| 902345 | 12-Aug-84 | 2014 | 250.00 | 216,020 | 86.46 | 149.70 | 0.00 | | | |
| 750244 | 15-Aug-84 | 2308 | 318.88 | 216,339 | 5.59 | 1.00 | 249.90 | | | |
| 902346 | 20-Aug-84 | 2014 | 250.00 | 216,589 | 86.49 | 149.70 | 0.00 | | | |
| 901452 | 21-Aug-84 | 0207 | 100.00 | 216,689 | 17.32 | 15.50 | 30.10 | | | |
| 750245 | 23-Aug-84 | 2308 | 25.61 | 216,714 | 4.97 | 0.50 | 15.61 | | | |
| STS014-A | 30-Aug-84 | 2109 | 521.53 | 217,236 | 13.74 | 401.50 | 0.00 | | | |
| STS014-B | 30-Aug-84 | 2018 | 521.67 | 217,757 | 13.34 | 401.70 | 0.00 | | | |
| STS014-C | 30-Aug-84 | 2021 | 521.78 | 218,279 | 13.75 | 401.60 | 0.00 | | | |
| 901453 | 31-Aug-84 | 0207 | 300.00 | 218,579 | 79.43 | 115.70 | 59.20 | | | |
| 901454 | 12-Sep-84 | 0207 | 100.00 | 218,679 | 17.26 | 15.50 | 30.10 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Considered by this Study Catastrophic Failures | Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902347 | 13-Sep-84 | 2014 | 250.00 | 218,929 | 48.84 | 149.70 | 0.00 | | | |
| 901455 | 21-Sep-84 | 0207 | 500.00 | 219,429 | 99.01 | 16.50 | 380.20 | | | |
| 901456 | 25-Sep-84 | 0207 | 595.05 | 220,024 | 5.16 | 0.50 | 585.15 | | | |
| 902348 | 28-Sep-84 | 2014 | 249.94 | 220,274 | 58.41 | 149.70 | 0.00 | | | |
| 901457 | 29-Sep-84 | 0207 | 499.92 | 220,774 | 5.04 | 0.50 | 490.02 | | | |
| 901458 | 5-Oct-84 | 0207 | 500.00 | 221,274 | 5.11 | 0.50 | 490.10 | | | |
| STS017-A | 5-Oct-84 | 2023 | 536.69 | 221,811 | 429.82 | 0.00 | 0.00 | | | |
| STS017-B | 5-Oct-84 | 2020 | 536.83 | 222,348 | 429.70 | 0.00 | 0.00 | | | |
| STS017-C | 5-Oct-84 | 2021 | 536.95 | 222,885 | 429.78 | 0.00 | 0.00 | | | |
| 902349 | 10-Oct-84 | 2014 | 250.00 | 223,135 | 58.49 | 149.70 | 0.00 | | | |
| 750246 | 11-Oct-84 | 2308 | 1.50 | 223,136 | 0.00 | 0.00 | 0.00 | | | |
| 750247 | 15-Oct-84 | 2308 | 1.50 | 223,138 | 0.00 | 0.00 | 0.00 | | | |
| 902350 | 16-Oct-84 | 2014 | 250.00 | 223,388 | 58.55 | 149.70 | 0.00 | | | |
| 750248 | 18-Oct-84 | 2308 | 10.27 | 223,398 | 5.24 | 0.48 | 0.00 | | | |
| 750249 | 22-Oct-84 | 2308 | 69.96 | 223,468 | 19.92 | 17.36 | 28.20 | | | |
| 902351 | 24-Oct-84 | 2014 | 250.00 | 223,718 | 58.16 | 149.64 | 0.00 | | | |
| 901459 | 26-Oct-84 | 0207 | 193.36 | 223,911 | 5.12 | 0.50 | 183.46 | | | |
| 902352 | 2-Nov-84 | 2014 | 250.00 | 224,161 | 58.16 | 149.72 | 0.00 | | | |
| STS019-A | 8-Nov-84 | 2109 | 519.53 | 224,681 | 21.20 | 387.30 | 0.00 | | | |
| STS019-B | 8-Nov-84 | 2018 | 519.67 | 225,200 | 21.24 | 387.10 | 0.00 | | | |
| STS019-C | 8-Nov-84 | 2012 | 519.79 | 225,720 | 21.36 | 387.10 | 0.00 | | | |
| 901460 | 12-Nov-84 | 0207 | 500.80 | 226,221 | 5.80 | 1.68 | 488.84 | | | |
| 902353 | 28-Nov-84 | 2014 | 4.52 | 226,226 | 0.29 | 0.00 | 0.00 | | | |
| 902354 | 1-Dec-84 | 2014 | 250.00 | 226,476 | 58.40 | 149.36 | 0.00 | | | |
| 901461 | 28-Dec-84 | 0207 | 90.00 | 226,566 | 39.76 | 16.32 | 29.36 | | | |
| 901462 | 5-Jan-85 | 0207 | 90.00 | 226,656 | 40.16 | 16.16 | 29.36 | | | |
| 901463 | 14-Jan-85 | 0207 | 250.04 | 226,906 | 80.16 | 15.80 | 149.68 | | | |
| 901464 | 17-Jan-85 | 0207 | 283.75 | 227,189 | 25.36 | 1.20 | 252.80 | | | |
| 750250 | 18-Jan-85 | 2308 | 70.01 | 227,259 | 20.04 | 16.40 | 29.16 | | | |
| 901465 | 19-Jan-85 | 0207 | 32.95 | 227,292 | 25.28 | 1.60 | 1.60 | | | |
| 901466 | 24-Jan-85 | 0207 | 500.08 | 227,792 | 59.60 | 1.84 | 434.28 | | | |
| STS020-A | 24-Jan-85 | 2109 | 517.02 | 228,309 | 24.08 | 389.50 | 0.00 | | | |
| STS020-B | 24-Jan-85 | 2018 | 517.15 | 228,827 | 23.72 | 389.62 | 0.00 | | | |
| STS020-C | 24-Jan-85 | 2012 | 517.27 | 229,344 | 24.20 | 389.30 | 0.00 | | | |

## SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901467 | 30-Jan-85 | 0207 | 586.82 | 229,931 | 26.32 | 2.12 | 554.00 | | | |
| 750251 | 1-Feb-85 | 2308 | 340.00 | 230,271 | 20.40 | 23.88 | 82.08 | | | |
| 901468 | 4-Feb-85 | 0207 | 203.86 | 230,474 | 25.32 | 1.20 | 172.92 | | | |
| 902355 | 6-Feb-85 | 2015 | 1.55 | 230,476 | 0.00 | 0.00 | 0.00 | | | |
| 750252 | 9-Feb-85 | 2308 | 340.01 | 230,816 | 21.08 | 24.08 | 81.80 | | | |
| 902356 | 11-Feb-85 | 2015 | 250.00 | 231,066 | 96.48 | 149.28 | 0.00 | | | |
| 750253 | 19-Feb-85 | 2308 | 177.32 | 231,243 | 5.36 | 1.56 | 166.00 | | | |
| 902357 | 19-Feb-85 | 2015 | 510.04 | 231,753 | 85.24 | 383.32 | 0.00 | | | |
| 750254 | 22-Feb-85 | 2308 | 300.00 | 232,053 | 6.44 | 279.40 | 0.00 | | | |
| 901469 | 23-Feb-85 | 2105 | 1.50 | 232,055 | 0.00 | 0.00 | 0.00 | | | |
| 750255 | 25-Feb-85 | 2308 | 300.00 | 232,355 | 6.20 | 141.00 | 139.20 | | | |
| 901470 | 25-Feb-85 | 2105 | 250.06 | 232,605 | 75.44 | 20.76 | 149.64 | | | |
| 901471 | 27-Feb-85 | 2105 | 503.00 | 233,108 | 107.24 | 11.32 | 380.20 | | | |
| 750256 | 1-Mar-85 | 2308 | 300.00 | 233,408 | 5.28 | 2.52 | 268.60 | | | |
| 901472 | 4-Mar-85 | 2105 | 520.00 | 233,928 | 99.84 | 415.88 | 0.00 | | | |
| 902358 | 5-Mar-85 | 2014 | 250.04 | 234,178 | 96.24 | 149.60 | 0.00 | | | |
| 750257 | 6-Mar-85 | 2308 | 300.00 | 234,478 | 5.12 | 22.00 | 249.08 | | | |
| 901473 | 6-Mar-85 | 2105 | 503.02 | 234,981 | 107.44 | 11.08 | 380.28 | | | |
| 902359 | 13-Mar-85 | 2014 | 250.04 | 235,231 | 96.44 | 149.40 | 0.00 | | | |
| 902360 | 16-Mar-85 | 2014 | 250.00 | 235,481 | 96.12 | 149.64 | 0.00 | | | |
| 901474 | 22-Mar-85 | 2105 | 503.06 | 235,984 | 107.20 | 11.72 | 379.76 | | | |
| 750258 | 23-Mar-85 | 2308 | 70.00 | 236,054 | 20.00 | 16.48 | 29.20 | | | |
| 902361 | 26-Mar-85 | 2014 | 250.08 | 236,304 | 58.60 | 149.48 | 0.00 | | | |
| 750259 | 27-Mar-85 | 2308 | 101.56 | 236,406 | 5.36 | 1.70 | 90.12 | X | | |
| STS023-A | 12-Apr-85 | 2109 | 538.23 | 236,944 | 421.74 | 0.00 | 0.00 | | | |
| STS023-B | 12-Apr-85 | 2018 | 538.33 | 237,482 | 422.02 | 0.00 | 0.00 | | | |
| STS023-C | 12-Apr-85 | 2012 | 538.47 | 238,021 | 422.02 | 0.00 | 0.00 | | | |
| 901475 | 17-Apr-85 | 2105 | 520.03 | 238,541 | 100.04 | 415.56 | 0.00 | | | |
| 902362 | 22-Apr-85 | 2024 | 1.50 | 238,542 | 0.00 | 0.00 | 0.00 | | | |
| 902363 | 24-Apr-85 | 2024 | 250.05 | 238,792 | 58.60 | 149.72 | 0.00 | | | |
| STS024-A | 29-Apr-85 | 2023 | 521.63 | 239,314 | 27.04 | 338.06 | 0.00 | | | |
| STS024-B | 29-Apr-85 | 2020 | 521.46 | 239,835 | 27.28 | 387.78 | 0.00 | | | |
| STS024-C | 29-Apr-85 | 2021 | 521.57 | 240,357 | 27.32 | 387.98 | 0.00 | | | |
| 902364 | 3-May-85 | 2024 | 250.00 | 240,607 | 58.64 | 149.64 | 0.00 | | | |

## SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902365 | 13-May-85 | 2024 | 380.41 | 240,987 | 7.28 | 331.60 | 0.00 | | | |
| 901476 | 21-May-85 | 2105 | 70.00 | 241,057 | 20.08 | 16.12 | 29.44 | | | |
| 901477 | 24-May-85 | 2105 | 250.00 | 241,307 | 75.44 | 20.60 | 149.64 | | | |
| 901478 | 1-Jun-85 | 2105 | 503.00 | 241,810 | 107.20 | 11.64 | 379.84 | | | |
| 901479 | 5-Jun-85 | 2105 | 503.00 | 242,313 | 107.20 | 11.48 | 379.96 | | | |
| 901480 | 7-Jun-85 | 2105 | 503.00 | 242,816 | 107.20 | 11.56 | 379.88 | | | |
| 901481 | 10-Jun-85 | 2105 | 520.06 | 243,336 | 99.84 | 415.84 | 0.00 | | | |
| 902366 | 17-Jun-85 | 2024 | 250.06 | 243,587 | 58.04 | 149.64 | 0.00 | | | |
| STS025-A | 17-Jun-85 | 2109 | 522.12 | 244,109 | 13.28 | 397.54 | 0.00 | | | |
| STS025-B | 17-Jun-85 | 2018 | 522.24 | 244,631 | 13.72 | 397.22 | 0.00 | | | |
| STS025-C | 17-Jun-85 | 2012 | 522.36 | 245,153 | 13.96 | 397.14 | 0.00 | | | |
| 902367 | 29-Jun-85 | 2024 | 250.00 | 245,403 | 57.92 | 149.44 | 0.00 | | | |
| 902368 | 2-Jul-85 | 2024 | 60.04 | 245,463 | 17.96 | 0.00 | 0.00 | | | |
| 901482 | 9-Jul-85 | 2105 | 520.00 | 245,983 | 99.88 | 415.80 | 0.00 | | | |
| STSA26-A | 12-Jul-85 | 2023 | 3.52 | 245,987 | 0.00 | 0.00 | 0.00 | | | |
| STSA26-B | 12-Jul-85 | 2020 | 1.74 | 245,989 | 0.00 | 0.00 | 0.00 | | | |
| STSA26-C | 12-Jul-85 | 2021 | 3.76 | 245,992 | 0.00 | 0.00 | 0.00 | | | |
| 901483 | 13-Jul-85 | 2105 | 520.00 | 246,512 | 100.04 | 415.64 | 0.00 | | | |
| 902369 | 17-Jul-85 | 2024 | 250.00 | 246,762 | 58.32 | 149.72 | 0.00 | | | |
| 901484 | 19-Jul-85 | 2105 | 603.06 | 247,365 | 12.28 | 1.40 | 585.00 | | | |
| 901485 | 24-Jul-85 | 2105 | 28.53 | 247,394 | 12.32 | 1.36 | 10.52 | | | |
| STS026-A | 29-Jul-85 | 2023 | 349.75 | 247,744 | 7.88 | 298.13 | 0.00 | | | |
| STS026-B | 29-Jul-85 | 2020 | 587.73 | 248,331 | 8.08 | 530.63 | 0.00 | | | |
| STS026-C | 29-Jul-85 | 2021 | 587.85 | 248,919 | 9.12 | 529.67 | 0.00 | | | |
| 901486 | 30-Jul-85 | 2105 | 520.00 | 249,439 | 99.68 | 416.00 | 0.00 | | | |
| 902370 | 31-Jul-85 | 2116 | 1.55 | 249,441 | 0.00 | 0.00 | 0.00 | | | |
| 902371 | 3-Aug-85 | 2116 | 249.84 | 249,691 | 38.52 | 20.88 | 149.32 | | | |
| 901487 | 4-Aug-85 | 2105 | 503.03 | 250,194 | 35.04 | 133.92 | 329.76 | | | |
| 901488 | 7-Aug-85 | 2105 | 502.96 | 250,697 | 103.24 | 10.20 | 385.24 | | | |
| 902372 | 9-Aug-85 | 2116 | 503.02 | 251,200 | 19.88 | 11.60 | 379.76 | | | |
| 901489 | 12-Aug-85 | 2105 | 302.04 | 251,502 | 20.96 | 276.76 | 0.00 | | | |
| 902373 | 13-Aug-85 | 2116 | 520.04 | 252,022 | 15.12 | 415.32 | 0.00 | | | |
| 902374 | 17-Aug-85 | 2116 | 225.54 | 252,247 | 8.32 | 186.44 | 0.00 | | | |
| STS027-A | 27-Aug-85 | 2109 | 513.92 | 252,761 | 12.64 | 412.82 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| STS027-B | 27-Aug-85 | 2018 | 514.04 | 253,275 | 13.84 | 411.82 | 0.00 | | | |
| STS027-C | 27-Aug-85 | 2012 | 514.16 | 253,789 | 13.48 | 412.14 | 0.00 | | | |
| 901490 | 31-Aug-85 | 2105 | 503.06 | 254,292 | 107.40 | 11.72 | 379.68 | | | |
| 902375 | 6-Sep-85 | 2116 | 466.03 | 254,758 | 38.96 | 120.36 | 19.48 | | | |
| 750260 | 7-Sep-85 | 2025 | 1.52 | 254 760 | 0.00 | 0.00 | 0.00 | | | |
| 901491 | 7-Sep-85 | 2105 | 503.05 | 255,263 | 107.40 | 11.32 | 380.04 | | | |
| 750261 | 12-Sep-85 | 2025 | 249.95 | 255,513 | 58.16 | 149.68 | 0.00 | | | |
| 902376 | 12-Sep-85 | 2116 | 466.08 | 255,979 | 38.56 | 120.68 | 19.36 | | | |
| FRF005-A | 12-Sep-85 | 2011 | 19.20 | 255,998 | 14.92 | 0.00 | 0.00 | | | |
| FRF005-B | 12-Sep-85 | 2019 | 20.50 | 256,019 | 16.20 | 0.00 | 0.00 | | | |
| FRF005-C | 12-Sep-85 | 2017 | 21.96 | 256,041 | 17.76 | 0.00 | 0.00 | | | |
| 902377 | 17-Sep-85 | 2116 | 503.06 | 256,544 | 19.92 | 11.48 | 379.84 | | | |
| 901492 | 19-Sep-85 | 2105 | 503.06 | 257,047 | 107.28 | 11.60 | 379.88 | | | |
| 902378 | 20-Sep-85 | 2116 | 761.08 | 257,808 | 205.60 | 1.64 | 511.44 | | | |
| 901493 | 24-Sep-85 | 2105 | 350.06 | 258,158 | 291.40 | 45.36 | 8.96 | | | |
| 902379 | 25-Sep-85 | 2116 | 503.04 | 258,661 | 19.56 | 10.32 | 385.24 | | | |
| STS028-A | 3-Oct-85 | 2011 | 518.28 | 259,179 | 11.80 | 416.74 | 0.00 | | | |
| STS028-B | 3-Oct-85 | 2019 | 518.40 | 259,698 | 11.44 | 417.18 | 0.00 | | | |
| STS028-C | 3-Oct-85 | 2017 | 518.52 | 260,216 | 11.64 | 417.02 | 0.00 | | | |
| 902380 | 7-Oct-85 | 2116 | 503.06 | 260,719 | 19.76 | 11.56 | 379.76 | | | |
| 750262 | 11-Oct-85 | 2025 | 250.00 | 260,969 | 56.72 | 1.68 | 149.44 | | | |
| 902381 | 14-Oct-85 | 2116 | 603.04 | 261,572 | 12.36 | 1.36 | 584.96 | | | |
| 901494 | 18-Oct-85 | 2026 | 1.50 | 261,574 | 0.00 | 0.00 | 0.00 | | | |
| 902382 | 19-Oct-85 | 2116 | 503.00 | 262,077 | 19.48 | 10.36 | 385.16 | | | |
| 901495 | 22-Oct-85 | 2026 | 250.04 | 262,327 | 38.88 | 207.04 | 0.00 | | | |
| 902383 | 26-Oct-85 | 2116 | 275.03 | 262,602 | 48.44 | 184.04 | 0.00 | | | |
| STS030-A | 30-Oct-85 | 2023 | 521.32 | 263,123 | 24.76 | 389.94 | 0.00 | | | |
| STS030-B | 30-Oct-85 | 2020 | 521.46 | 263,645 | 25.32 | 389.74 | 0.00 | | | |
| STS030-C | 30-Oct-85 | 2021 | 521.58 | 264,166 | 25.24 | 389.98 | 0.00 | | | |
| 902384 | 5-Nov-85 | 2116 | 250.03 | 264,416 | 58.32 | 149.16 | 0.00 | | | |
| 902385 | 20-Nov-85 | 2116 | 250.00 | 264,666 | 38.52 | 20.60 | 149.68 | | | |
| STS031-A | 26-Nov-85 | 2011 | 517.65 | 265,184 | 13.20 | 413.86 | 0.00 | | | |
| STS031-B | 26-Nov-85 | 2019 | 517.77 | 265,702 | 13.20 | 413.82 | 0.00 | | | |
| STS031-C | 26-Nov-85 | 2017 | 517.88 | 266,220 | 13.36 | 413.78 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902386 | 11-Dec-85 | 2026 | 18.21 | 266,238 | 12.32 | 1.60 | 0.00 | | | |
| 902387 | 20-Dec-85 | 2026 | 503.06 | 266,741 | 20.24 | 31.72 | 349.88 | | | |
| 902388 | 23-Dec-85 | 2026 | 200.00 | 266,941 | 85.52 | 9.48 | 100.84 | | | |
| STS032-A | 12-Jan-86 | 2015 | 508.00 | 267,449 | 12.24 | 410.14 | 0.00 | | | |
| STS032-B | 12-Jan-86 | 2018 | 508.12 | 267,957 | 12.04 | 410.50 | 0.00 | | | |
| STS032-C | 12-Jan-86 | 2109 | 508.26 | 268,465 | 12.24 | 410.14 | 0.00 | | | |
| 902389 | 17-Jan-86 | 2022 | 250.00 | 268,715 | 38.64 | 20.48 | 149.84 | | | |
| STS033-A | 28-Jan-86 | 2023 | 79.40 | 268,795 | 8.00 | 31.92 | 0.00 | | | |
| STS033-B | 28-Jan-86 | 2020 | 79.56 | 268,874 | 8.16 | 31.92 | 0.00 | | | |
| STS033-C | 28-Jan-86 | 2021 | 79.62 | 268,954 | 8.24 | 32.00 | 0.00 | | | |
| 750263 | 11-Jun-86 | 2025 | 1.50 | 268,955 | 0.00 | 0.00 | 0.00 | | | |
| 750264 | 24-Jun-86 | 2025 | 40.00 | 268,995 | 12.12 | 23.72 | 0.00 | | | |
| 902390 | 26-Jun-86 | 2106 | 1.50 | 268,997 | 0.00 | 0.00 | 0.00 | | | |
| 902391 | 16-Jul-86 | 2106 | 250.00 | 269,247 | 95.84 | 149.96 | 0.00 | | | |
| 902392 | 25-Jul-86 | 2106 | 520.00 | 269,767 | 14.76 | 404.92 | 0.00 | | | |
| 902393 | 23-Aug-86 | 2106 | 520.00 | 270,287 | 14.80 | 415.88 | 0.00 | | | |
| 901496 | 13-Sep-86 | 2105 | 1.50 | 270,288 | 0.00 | 0.00 | 0.00 | | | |
| 901497 | 4-Oct-86 | 2105 | 520.00 | 270,808 | 16.08 | 499.76 | 0.00 | | | |
| 750265 | 8-Oct-86 | 2025 | 10.04 | 270,818 | 5.80 | 0.00 | 0.00 | | | |
| 901498 | 14-Oct-86 | 2105 | 520.00 | 271,338 | 16.00 | 499.72 | 0.00 | | | |
| 750266 | 16-Oct-86 | 2025 | 6.00 | 271,344 | 1.76 | 0.00 | 0.00 | | | |
| 901499 | 18-Oct-86 | 2105 | 520.00 | 271,864 | 15.96 | 499.76 | 0.00 | | | |
| 901500 | 25-Oct-86 | 2105 | 520.00 | 272,384 | 15.88 | 499.88 | 0.00 | | | |
| 901501 | 6-Nov-86 | 2105 | 519.12 | 272,903 | 15.04 | 499.88 | 0.00 | | | |
| 902394 | 11-Nov-86 | 2106 | 1.50 | 272,905 | 0.00 | 0.00 | 0.00 | | | |
| 902395 | 15-Nov-86 | 2106 | 1.50 | 272,906 | 0.00 | 0.00 | 0.00 | | | |
| 750267 | 24-Nov-86 | 2012 | 80.00 | 272,986 | 17.28 | 58.52 | 0.00 | | | |
| 902396 | 24-Nov-86 | 2106 | 1.50 | 272,988 | 0.00 | 0.00 | 0.00 | | | |
| 901502 | 26-Nov-86 | 2105 | 520.00 | 273,508 | 16.04 | 499.68 | 0.00 | | | |
| 901503 | 3-Dec-86 | 2105 | 520.03 | 274,028 | 99.72 | 416.00 | 0.00 | | | |
| 750268 | 6-Dec-86 | 2012 | 213.00 | 274,241 | 42.04 | 13.72 | 0.00 | | | |
| 901504 | 6-Dec-86 | 2105 | 520.00 | 274,761 | 99.96 | 415.72 | 0.00 | | | |
| 902397 | 7-Dec-86 | 2106 | 520.00 | 275,281 | 14.76 | 415.92 | 0.00 | | | |
| 901505 | 9-Dec-86 | 2105 | 520.00 | 275,801 | 99.92 | 415.72 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902398 | 11-Dec-86 | 2106 | 520.00 | 276,321 | 16.24 | 499.56 | 0.00 | | | |
| 750269 | 12-Dec-86 | 2012 | 5.00 | 276,326 | 0.68 | 0.00 | 0.00 | | | |
| 901506 | 12-Dec-86 | 2105 | 520.00 | 276,846 | 99.68 | 416.00 | 0.00 | | | |
| 902399 | 15-Dec-86 | 2106 | 600.00 | 277,446 | 16.04 | 579.72 | 0.00 | | | |
| 901507 | 16-Dec-86 | 2105 | 590.06 | 278,036 | 100.00 | 485.80 | 0.00 | | | |
| 750270 | 18-Dec-86 | 2012 | 321.00 | 278,357 | 38.68 | 38.84 | 35.96 | | | |
| 902400 | 18-Dec-86 | 2106 | 520.00 | 278,877 | 11.08 | 504.72 | 0.00 | | | |
| 750271 | 23-Dec-86 | 2012 | 250.00 | 279,127 | 28.76 | 15.72 | 3.00 | | | |
| 901508 | 30-Dec-86 | 2105 | 520.00 | 279,647 | 15.88 | 499.80 | 0.00 | | | |
| 902401 | 2-Jan-87 | 2106 | 520.00 | 280,167 | 16.12 | 499.68 | 0.00 | | | |
| 901509 | 5-Jan-87 | 2105 | 520.00 | 280,687 | 15.88 | 499.76 | 0.00 | | | |
| 902402 | 10-Jan-87 | 2106 | 520.00 | 281,207 | 16.08 | 499.68 | 0.00 | | | |
| 750272 | 12-Jan-87 | 2012 | 300.00 | 281,507 | 38.64 | 133.60 | 0.00 | | | |
| 901510 | 12-Jan-87 | 2105 | 520.00 | 282,027 | 16.00 | 499.64 | 0.00 | | | |
| 902403 | 13-Jan-87 | 2106 | 520.00 | 282,547 | 16.12 | 499.64 | 0.00 | | | |
| 901511 | 15-Jan-87 | 2105 | 520.00 | 283,067 | 15.88 | 499.76 | 0.00 | | | |
| 902404 | 16-Jan-87 | 2106 | 520.00 | 283,587 | 7.64 | 499.64 | 0.00 | | | |
| 750273 | 17-Jan-87 | 2012 | 300.00 | 283,887 | 81.08 | 139.64 | 0.00 | | | |
| 750274 | 23-Jan-87 | 2012 | 300.00 | 284,187 | 16.48 | 279.28 | 0.00 | | | |
| 901512 | 27-Jan-87 | 2105 | 5.06 | 284,192 | 0.80 | 0.00 | 0.00 | | | |
| 901513 | 30-Jan-87 | 2105 | 520.00 | 284,712 | 99.84 | 415.88 | 0.00 | | | |
| 750275 | 31-Jan-87 | 2012 | 300.00 | 285,012 | 16.12 | 279.64 | 0.00 | | | |
| 902405 | 31-Jan-87 | 2106 | 200.00 | 285,212 | 7.64 | 179.68 | 0.00 | | | |
| 902406 | 3-Feb-87 | 2106 | 200.00 | 285,412 | 7.44 | 179.72 | 0.00 | | | |
| 902407 | 6-Feb-87 | 2106 | 200.00 | 285,612 | 7.60 | 179.68 | 0.00 | | | |
| 901514 | 11-Feb-87 | 2105 | 520.00 | 286,132 | 99.68 | 416.04 | 0.00 | | | |
| 901515 | 14-Feb-87 | 2105 | 503.00 | 286,635 | 107.28 | 11.16 | 380.28 | | | |
| 902408 | 14-Feb-87 | 2106 | 200.00 | 286,835 | 7.64 | 179.60 | 0.00 | | | |
| 901516 | 17-Feb-87 | 2105 | 761.00 | 287,596 | 243.56 | 2.24 | 510.92 | | | |
| 902409 | 19-Feb-87 | 2106 | 200.00 | 287,796 | 7.52 | 179.64 | 0.00 | | | |
| 901517 | 24-Feb-87 | 2105 | 603.00 | 288,399 | 12.51 | 1.25 | 584.96 | | | |
| 750276 | 2-Mar-87 | 0210 | 1.50 | 288,401 | 0.00 | 0.00 | 0.00 | | | |
| 901518 | 2-Mar-87 | 2105 | 520.00 | 288,921 | 99.97 | 415.71 | 0.00 | | | |
| 902410 | 2-Mar-87 | 2106 | 520.00 | 289,441 | 15.20 | 415.64 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 902411 | 11-Mar-87 | 2106 | 520.00 | 289,961 | 15.08 | 415.60 | 0.00 | | | |
| 750277 | 12-Mar-87 | 0210 | 200.00 | 290,161 | 11.92 | 183.92 | 0.00 | | | |
| 902412 | 13-Mar-87 | 2106 | 520.00 | 290,681 | 15.24 | 415.44 | 0.00 | | | |
| 901519 | 14-Mar-87 | 2011 | 1.50 | 290,682 | 0.00 | 0.00 | 0.00 | | | |
| 750278 | 16-Mar-87 | 0210 | 200.00 | 290,882 | 12.00 | 183.84 | 0.00 | | | |
| 902413 | 17-Mar-87 | 2106 | 503.00 | 291,385 | 20.04 | 11.28 | 380.16 | | | |
| 750279 | 19-Mar-87 | 0210 | 200.00 | 291,585 | 12.00 | 183.80 | 0.00 | | | |
| 901520 | 19-Mar-87 | 2011 | 200.00 | 291,785 | 16.28 | 129.92 | 49.36 | | | |
| 902414 | 23-Mar-87 | 2106 | 567.00 | 292,352 | 12.48 | 1.08 | 549.24 | | | |
| 750280 | 26-Mar-87 | 0210 | 200.00 | 292,552 | 11.96 | 183.80 | 0.00 | | | |
| 902415 | 31-Mar-87 | 2106 | 520.00 | 293,072 | 15.36 | 415.28 | 0.00 | | | |
| 750281 | 2-Apr-87 | 0210 | 200.00 | 293,272 | 11.84 | 183.96 | 0.00 | | | |
| 901521 | 4-Apr-87 | 2011 | 320.00 | 293,592 | 96.04 | 210.00 | 9.64 | | | |
| 750282 | 6-Apr-87 | 0210 | 200.00 | 293,792 | 12.00 | 183.76 | 0.00 | | | |
| 902416 | 9-Apr-87 | 2106 | 520.00 | 294,312 | 15.04 | 415.64 | 0.00 | | | |
| 902417 | 21-Apr-87 | 2106 | 797.00 | 295,109 | 206.00 | 1.60 | 547.48 | | | |
| 750283 | 22-Apr-87 | 0210 | 300.00 | 295,409 | 12.00 | 283.72 | 0.00 | | | |
| 901522 | 24-Apr-87 | 2105 | 520.00 | 295,929 | 99.72 | 415.92 | 0.00 | | | |
| 902418 | 28-Apr-87 | 2106 | 750.00 | 296,679 | 177.96 | 491.96 | 0.00 | | | |
| 750284 | 29-Apr-87 | 0210 | 300.00 | 296,979 | 11.92 | 283.84 | 0.00 | | | |
| 901523 | 30-Apr-87 | 2105 | 520.00 | 297,499 | 218.12 | 297.52 | 0.00 | | | |
| 902419 | 1-May-87 | 2106 | 90.38 | 297,590 | 8.20 | 51.68 | 0.00 | | | |
| 901524 | 9-May-87 | 2105 | 850.00 | 298,440 | 299.68 | 545.96 | 0.00 | | | |
| 901525 | 14-May-87 | 2105 | 250.00 | 298,690 | 34.52 | 211.08 | 0.00 | | | |
| 902420 | 18-May-87 | 2106 | 520.00 | 299,210 | 11.76 | 477.74 | 0.00 | | | |
| 901526 | 20-May-87 | 2105 | 520.00 | 299,730 | 137.52 | 378.08 | 0.00 | | | |
| 750285 | 21-May-87 | 0210 | 223.56 | 299,953 | 6.64 | 1.16 | 211.96 | | | |
| 902421 | 26-May-87 | 2106 | 680.00 | 300,633 | 7.24 | 668.60 | 0.00 | | | |
| 902422 | 29-May-87 | 2106 | 503.06 | 301,136 | 20.04 | 11.16 | 380.24 | | | |
| 901527 | 30-May-87 | 2105 | 700.00 | 301,836 | 94.44 | 601.12 | 0.00 | | | |
| 902423 | 3-Jun-87 | 2106 | 520.00 | 302,356 | 195.44 | 294.00 | 0.00 | | | |
| 901528 | 4-Jun-87 | 2105 | 503.00 | 302,859 | 107.28 | 11.28 | 380.04 | | | |
| 902424 | 6-Jun-87 | 2106 | 275.00 | 303,134 | 7.24 | 263.56 | 0.00 | | | |
| 901529 | 8-Jun-87 | 2105 | 603.00 | 303,737 | 12.28 | 1.28 | 585.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901530 | 11-Jun-87 | 2105 | 503.00 | 304,240 | 107.28 | 11.32 | 380.04 | | | |
| 902425 | 11-Jun-87 | 2106 | 520.00 | 304,760 | 14.76 | 415.92 | 0.00 | | | |
| 901531 | 13-Jun-87 | 2105 | 520.05 | 305,280 | 100.12 | 415.48 | 0.00 | | | |
| 750286 | 16-Jun-87 | 0210 | 300.00 | 305,580 | 11.84 | 283.72 | 0.00 | | | |
| 901532 | 17-Jun-87 | 2105 | 520.00 | 306,100 | 41.56 | 474.06 | 0.00 | | | |
| 750287 | 19-Jun-87 | 0210 | 300.00 | 306,400 | 12.88 | 265.24 | 0.00 | | | |
| 902426 | 23-Jun-87 | 2106 | 1000.00 | 307,400 | 307.08 | 668.68 | 0.00 | | | |
| 750288 | 25-Jun-87 | 0210 | 4.40 | 307,405 | 0.00 | 0.00 | 0.00 | | | |
| 90'533 | 25-Jun-87 | 2105 | 520.00 | 307,925 | 99.92 | 415.64 | 0.00 | | | |
| 902427 | 26-Jun-87 | 2106 | 138.36 | 308,063 | 59.72 | 74.36 | 0.00 | X | X | X |
| 902428 | 1-Jul-87 | 2106 | 204.12 | 308,267 | 82.88 | 114.06 | 0.00 | X | X | X |
| 750289 | 6-Jul-87 | 0210 | 300.00 | 308,567 | 11.92 | 283.68 | 0.00 | | | |
| 901534 | 6-Jul-87 | 2105 | 520.00 | 309,087 | 224.72 | 290.92 | 0.00 | | | |
| 750290 | 9-Jul-87 | 0210 | 300.00 | 309,387 | 11.96 | 283.64 | 0.00 | | | |
| 750291 | 16-Jul-87 | 0210 | 300.00 | 309,687 | 12.04 | 283.56 | 0.00 | | | |
| 901535 | 18-Jul-87 | 2105 | 761.00 | 310,448 | 213.08 | 32.04 | 511.44 | | | |
| 750292 | 23-Jul-87 | 0210 | 100.00 | 310,548 | 11.88 | 83.68 | 0.00 | | | |
| 750293 | 28-Jul-87 | 0210 | 100.00 | 310,648 | 11.88 | 83.76 | 0.00 | | | |
| 750294 | 31-Jul-87 | 0210 | 100.00 | 310,748 | 11.80 | 83.84 | 0.00 | | | |
| 750295 | 4-Aug-87 | 0210 | 99.96 | 310,848 | 11.80 | 83.80 | [illegible] | | | |
| 901536 | 6-Aug-87 | 2105 | 520.00 | 311,368 | 99.92 | 415.66 | 0.00 | | | |
| 750296 | 7-Aug-87 | 0210 | 99.96 | 311,468 | 12.00 | 83.60 | 0.00 | | | |
| 902429 | 11-Aug-87 | 2027 | 1.50 | 311,469 | 0.00 | 0.00 | 0.00 | | | |
| 750297 | 12-Aug-87 | 0210 | 100.00 | 311,569 | 11.84 | 83.76 | 0.00 | | | |
| 901537 | 12-Aug-87 | 2105 | 656.66 | 312,226 | 454.92 | 197.36 | 0.00 | | | |
| 750298 | 1-Sep-87 | 0210 | 149.96 | 312,376 | 12.08 | 133.64 | 0.00 | | | |
| 750299 | 4-Sep-87 | 0210 | 210 | 312,586 | 12.04 | 193.68 | 0.00 | | | |
| 901538 | 4-Sep-87 | 0211 | 1.5 | 312,588 | 0.00 | 0.00 | 0.00 | | | |
| 901539 | 12-Sep-87 | 0211 | 300 | 312,888 | 16.00 | 279.68 | 0.00 | | | |
| 901540 | 15-Sep-87 | 0211 | 300.00 | 313,188 | 16.04 | 279.56 | 0.00 | | | |
| 902430 | 16-Sep-87 | 2027 | 250.00 | 313,438 | 29.92 | 144.76 | 19.52 | | | |
| 750300 | 17-Sep-87 | 0210 | 6.00 | 313,444 | 1.72 | 0.00 | 0.00 | | | |
| 901541 | 17-Sep-87 | 0211 | 300.00 | 313,744 | 15.96 | 279.68 | 0.00 | | | |
| 901542 | 19-Sep-87 | 0211 | 300.00 | 314,044 | 15.92 | 279.68 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901543 | 21-Sep-87 | 0211 | 300.00 | 314,344 | 15.96 | 279.68 | 0.00 | | | |
| 901544 | 23-Sep-87 | 0211 | 300.00 | 314,644 | 15.92 | 279.68 | 0.00 | | | |
| 901545 | 26-Sep-87 | 0211 | 210.00 | 314,854 | 18.12 | 187.60 | 0.00 | | | |
| 901546 | 30-Sep-87 | 0211 | 250.00 | 315,104 | 30.60 | 165.84 | 49.20 | | | |
| 901547 | 3-Oct-87 | 0211 | 135.00 | 315,239 | 16.00 | 114.60 | 0.00 | | | |
| 901548 | 5-Oct-87 | 0211 | 250.00 | 315,489 | 16.00 | 229.68 | 0.00 | | | |
| 902431 | 10-Oct-87 | 2027 | 520.00 | 316,009 | 21.24 | 348.92 | 51.44 | | | |
| 902432 | 28-Oct-87 | 2022 | 1.50 | 316,010 | 0.00 | 0.00 | 0.00 | | | |
| 902433 | 6-Nov-87 | 2022 | 250.00 | 316,260 | 29.92 | 144.88 | 19.52 | | | |
| 750301 | 8-Nov-87 | 2105 | 280.00 | 316,540 | 11.92 | 263.72 | 0.00 | | | |
| 901549 | 10-Nov-87 | 2019 | 1.50 | 316,542 | 0.00 | 0.00 | 0.00 | | | |
| 750302 | 12-Nov-87 | 2105 | 280.00 | 316,822 | 16.56 | 1.84 | 257.24 | | | |
| 750303 | 17-Nov-87 | 2105 | 280.00 | 317,102 | 12.00 | 263.64 | 0.00 | | | |
| 750304 | 21-Nov-87 | 2105 | 280.00 | 317,382 | 12.00 | 263.64 | 0.00 | | | |
| 902434 | 21-Nov-87 | 2022 | 520.00 | 317,902 | 20.92 | 348.88 | 51.56 | | | |
| 901550 | 22-Nov-87 | 2019 | 250.00 | 318,152 | 67.12 | 144.88 | 19.72 | | | |
| 901551 | 28-Nov-87 | 2019 | 520.00 | 318,672 | 54.40 | 352.68 | 51.52 | | | |
| 750305 | 4-Dec-87 | 2105 | 280.00 | 318,952 | 12.04 | 263.60 | 0.00 | | | |
| 750306 | 8-Dec-87 | 2105 | 250.00 | 319,202 | 16.56 | 1.84 | 227.28 | | | |
| 902435 | 10-Dec-87 | 2028 | 1.50 | 319,203 | 0.00 | 0.00 | 0.00 | | | |
| 902436 | 15-Dec-87 | 2028 | 250.00 | 319,453 | 29.76 | 114.32 | 50.20 | | | |
| 750307 | 19-Dec-87 | 2105 | 280.00 | 319,733 | 46.52 | 1.88 | 227.24 | | | |
| 750308 | 23-Dec-87 | 2105 | 280.00 | 320,013 | 42.04 | 233.56 | 0.00 | | | |
| 902437 | 23-Dec-87 | 2028 | 520.00 | 320,533 | 20.72 | 349.00 | 51.72 | | | |
| 901552 | 29-Dec-87 | 2027 | 754.00 | 321,287 | 7.72 | 468.52 | 0.00 | | | |
| 750309 | 15-Jan-88 | 2105 | 0.50 | 321,288 | 0.00 | 0.00 | 0.00 | | | |
| 901553 | 22-Jan-88 | 0211 | 520.00 | 321,808 | 102.68 | 360.40 | 52.60 | | | |
| 750310 | 23-Jan-88 | 2105 | 10.12 | 321,818 | 5.72 | 0.00 | 0.00 | | | |
| 902438 | 24-Jan-88 | 2029 | 1.50 | 321,819 | 0.00 | 0.00 | 0.00 | | | |
| 901554 | 27-Jan-88 | 0211 | 520.00 | 322,339 | 100.04 | 415.68 | 0.00 | | | |
| 750311 | 29-Jan-88 | 2105 | 300.00 | 322,639 | 11.40 | 264.96 | 19.20 | | | |
| 901555 | 3-Feb-88 | 0211 | 519.96 | 323,159 | 99.68 | 415.80 | 0.00 | | | |
| 902439 | 9-Feb-88 | 2029 | 250.00 | 323,409 | 29.84 | 109.64 | 51.84 | | | |
| 750312 | 10-Feb-88 | 2105 | 9.96 | 323,419 | 5.24 | 0.00 | 0.00 | | | |

SSME Chronological Experience with Power Levels

| Test/Flt Number | Date | Engn | Duratn per test (sec) | Program Exprnc cumulatv (sec) | Power Level Exposure (%) 100-103 per test (sec) | 104-108 per test (sec) | 109+ per test (sec) | Catastrophic Failures | Considered by this Study: Applicable Major Incidents | Applicable Catastrophic Failures |
|---|---|---|---|---|---|---|---|---|---|---|
| 901556 | 10-Feb-88 | 0211 | 519.88 | 323,939 | 99.52 | 415.72 | 0.00 | | | |
| 901557 | 14-Feb-88 | 0211 | 502.96 | 324,442 | 107.08 | 11.16 | 380.28 | | | |
| 901558 | 18-Feb-88 | 0211 | 503.00 | 324,945 | 106.84 | 11.20 | 380.40 | | | |
| 902440 | 19-Feb-88 | 2029 | 519.96 | 325,465 | 21.00 | 348.20 | 52.32 | | | |
| 901559 | 20-Feb-88 | 0211 | 602.96 | 326,068 | 32.04 | 3.12 | 563.28 | | | |
| 901560 | 25-Feb-88 | 0211 | 572.96 | 326,641 | 99.64 | 468.76 | 0.00 | | | |
| 902441 | 4-Mar-88 | 2029 | 250.00 | 326,891 | 21.80 | 147.12 | 51.36 | | | |
| 901561 | 5-Mar-88 | 0211 | 519.96 | 327,411 | 99.76 | 415.60 | 0.00 | | | |
| 901562 | 10-Mar-88 | 0211 | 519.96 | 327,931 | 99.84 | 415.48 | 0.00 | | | |
| 750313 | 21-Mar-88 | 0208 | 1.50 | 327,932 | 0.00 | 0.00 | 0.00 | | | |
| 901563 | 21-Mar-88 | 0211 | 20.00 | 327,952 | 7.00 | 8.40 | 0.00 | | | |
| 902442 | 23-Mar-88 | 2030 | 1.55 | 327,954 | 0.00 | 0.00 | 0.00 | | | |
| 750314 | 25-Mar-88 | 0208 | 10.00 | 327,964 | 5.68 | 0.00 | 0.00 | | | |
| 902443 | 28-Mar-88 | 2030 | 300.00 | 328,264 | 29.88 | 109.92 | 51.68 | | | |
| 901564 | 29-Mar-88 | 0211 | 519.94 | 328,784 | 488.52 | 26.66 | 0.00 | | | |
| 904001 | 30-Mar-88 | 2206 | 1.50 | 328,785 | 0.00 | 0.00 | 0.00 | | | |
| 750315 | 31-Mar-88 | 0208 | 140.96 | 328,926 | 95.84 | 40.88 | 0.00 | | | |
| 901565 | 5-Apr-88 | 0211 | 622.96 | 329,549 | 34.68 | 580.28 | 0.00 | | | |
| 901566 | 8-Apr-88 | 0211 | 520.00 | 330,069 | 99.56 | 415.76 | 0.00 | | | |
| 904002 | 9-Apr-88 | 2206 | 25.00 | 330,094 | 20.24 | 0.00 | 0.00 | | | |
| 902444 | 10-Apr-88 | 2030 | 520.00 | 330,614 | 20.96 | 348.76 | 51.76 | | | |
| 901567 | 16-Apr-88 | 0211 | 519.96 | 331,134 | 100.04 | 415.28 | 0.00 | | | |
| 901568 | 19-Apr-88 | 0211 | 502.96 | 331,637 | 107.00 | 11.04 | 380.28 | | | |
| 904003 | 20-Apr-88 | 2206 | 220.00 | 331,857 | 15.96 | 199.40 | 0.00 | | | |

# Appendix A.2

## A Quick Calculation of the Effect of Failure Correlation Factor vs. Engine Out Capability

A.2 CORRELATION vs ENGINE OUT CAPABILITY

A preliminary trade off study of single large liquid rocket engines vs "clustering" with reliability as the driver follows. Weight and cost as well as engine out capability is also considered but not calculated.

Let,

R1 = rocket engine reliability excluding plumbing to tanks.

R2 = reliability of plumbing.

Assume a single engine plumbing reliability of R2 = 0.999 and that increases in numbers of rockets produce directly proportional increases in plumbing complexity.
Since reliability decreases with increasing complexity then if,

$n := 1 \,..16$ the total number of rocket engines

$R2_n := \exp(n \cdot \ln(0.999))$

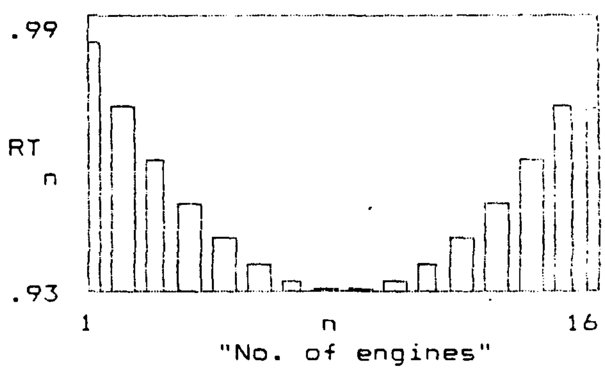
Since smaller "state of the art" engines are more mature thus possibly more reliable then R1 increases as n (the no. of engines) increases. This is because the more engines there are, the smaller they are.

$R1_n :=$

| $R1_n$ |
|---|
| .985 |
| .986 |
| .987 |
| .988 |
| .989 |
| .99 |
| .991 |
| .992 |
| .993 |
| .994 |
| .995 |
| .996 |
| .997 |
| .998 |
| .999 |
| .9991 |

| $R1_n^{\,n}$ | $R2_n$ |
|---|---|
| 0.985 | 0.999 |
| 0.972196 | 0.998001 |
| 0.9615048 | 0.997003 |
| 0.9528571 | 0.996006 |
| 0.9461968 | 0.99501 |
| 0.9414801 | 0.994015 |
| 0.9386757 | 0.993021 |
| 0.9377636 | 0.9920279 |
| 0.9387355 | 0.9910359 |
| 0.9415944 | 0.9900449 |
| 0.9463546 | 0.9890548 |
| 0.953042 | 0.9880658 |
| 0.9616943 | 0.9870777 |
| 0.9723611 | 0.9860906 |
| 0.9851045 | 0.9851045 |
| 0.9856968 | 0.9841194 |

$RT_n := R2_n \cdot R1_n^{\,n}$




$RT_8 = 0.9302877$ minimum reliability with 8 engines and NO engine out capability.

Consider now engine out capability:

if the number of engines varies from 4 to 16,

m = the total no. of engines

k = the maximum engine out capability

RS = total reliability with engine out capability.

C := 1.0 cost



W := 1.0 weight

$m := 4$

$R1_m :=$

| |
|---|
| .985 |
| .986 |
| .987 |
| .988 |
| .989 |
| .99 |
| .991 |
| .992 |
| .993 |
| .994 |
| .995 |
| .996 |
| .997 |
| .998 |
| .999 |
| .9991 |

$R2_m := \exp(m \ln(0.999))$

Now let.

$k := 3 ..4$ engines required for success

$$RE_k := \sum_k \left[ \frac{m!}{(m-k)!\, k!} \right] {R1_m}^k \left(1 - R1_m\right)^{m-k}$$

$RS_k := W\ C\ RE_k\ R2_m \qquad RS_4 = 0.9946881$

Let REC = reliability with correlated failures

$j := 1 ..7$ = the number of correlated failures

$$REC_j := \left(1 - \frac{j}{1000}\right)^4$$ ,for four engines

| $REC_j$ |
|---|
| 0.996006 |
| 0.992024 |
| 0.9880539 |
| 0.9840957 |
| 0.9801495 |
| 0.9762151 |
| 0.9722926 |

Thus 4 engines are no better than 1 if the correlation factor is between 20 and 30% as shown below.

$RT_j := REC_j\ RS_4$

| $RT_j$ |
|---|
| 0.9907153 |
| 0.9867545 |
| 0.9828055 |
| 0.9788684 |
| 0.9749431 |
| 0.9710296 |
| 0.9671279 |

Not only are four engines no better than one under the above conditions, three or two engines are also no better. In fact the correlation factor drives the results and begins to do so at about 15%.

Time did not allow a thorough study of the effects of cost or weight. In fact the entire subject is complex enough to warrant a separate study.

One could easily envision that an increase in the number of engines, plumbing and detection apparatus would increase weight thus reduce payload and might quickly render a clustered system uneconomical.

The purpose of this brief set of calculations is not to draw conclusions but that correlation factors of about 15% are definitely a "red flag" that warrants further study. It appears that liquid engine manufacturers are overly optimistic about correlation factors.

# Appendix A.3

# Reliability Analysis of Current US Launch Vehicles

Yu Shen
SAIC, Division 265, New York

December 21, 1988

# TABLE OF CONTENTS

## SUMMARY

This report contains reliability data for the following families of United States launch vehicles: Thor/ Delta, Titan, Atlas, the Saturn "Family", the Scout "Family", and the Space Shuttle.

The reliability data was obtained through the statistical models and procedures described in Section 2.0 as applied to the "Launch Vehicle Failure History Data Base" compiled by C.T. Clague of the Aerospace Corporation and other data sources given in the bibliography. The results of the analysis are summarized in the following table.

The statistical model and algorithm contained in this report is unique and is the only technique except for D. Lloyd's model that has been developed expressly for launch vehicles. It provides conservative reliability estimates during the "early launch" period of development. It also converges to the same value obtained by D. Lloyd when a sufficiently large number of launches and or tests have been attained. Unlike D. Lloyd's method, it does not require judgement as to whether or not a failure has been corrected nor does it require that component failure mode be known.

## OBJECTIVE AND BACKGROUND

The objective of this report is to produce a statistical model and algorithm which can estimate launch vehicle reliability based solely on attribute data that presently exists. In addition, the methodology is to serve as a means of estimating stage and system reliability. A secondary objective is to use the model as a means of predicting the reliability of new systems.

Presently existing methodologies do not meet the objectives cited above.

By way of background, the first attempts to measure launch system reliability were made in order to either ascertain what level of reliability had been attained at a given point especially prior to customer "buy off" or acceptance.

In the 1960's the most widely accepted approach was to assume that each test or launch was independent of all others. Using this assumption, one could easily calculate the reliability at any given level of confidence using the Binomial distribution. It became obvious, however, that reliability and confidence levels above 90% would require an inordinately large number of tests. In the early 70's Bayesian analysis was introduced. However, due to the subjective nature of prior distributions which rely on expert judgement rather than direct results from experiments and tests, the Bayesian approach did not receive wide acceptance in the aerospace industry.

In recent years D. Lloyd of TRW began developing a methodology that does require judgement, but the judgement is based solely on evidence that the propensity for certain failure modes to occur has been reduced by redesign and retest.

Dr. D. Lloyd's method appears to be the most recent attempt made to estimate reliability or developmental environment which includes Reliability Growth until now.

The methodology developed for this study is discussed in Section 2.0 of this report and is an approach which has some attractive features not found in other methods. This methodology was applied to the historical data obtained during the course of the study to produce the tables of reliability data which follow. A summary of all the results is given in Table A.2 and results for individual launch vehicle failures are indicated in Tables A.2a through A.2f.

## TABLE A.2: RELIABILITY COMPARISON OF U.S. LAUNCH VEHICLE FAMILIES

| | Vehicle Name / Data Collection Period | Thor / Delta: Thor 57-83 | Thor / Delta: Delta 60-87 | Thor / Delta: Combine 57-87 | Titan: Titan I 59-65 | Titan: Titan II 62-76 | Titan: Titan III 64-87 | Titan: Titan 34D 82-87 | Titan: Combine 59-87 |
|---|---|---|---|---|---|---|---|---|---|
| | Success Ratio: Mean | 0.8982 | 0.9402 | 0.9192 | 0.6427 | 0.8864 | 0.9408 | 0.7365 | 0.8013 |
| | 5% | 0.8750 | 0.9110 | 0.8789 | 0.5585 | 0.8323 | 0.9058 | 0.4878 | 0.8075 |
| | 95% | 0.9181 | 0.9615 | 0.9551 | 0.7202 | 0.9272 | 0.9651 | 0.8980 | 0.9546 |
| STAGE NO. | Stage 0 | 0.9965 | 0.9950 | | | | 0.9946 | 0.8678 | |
| | Stage 1/2 | | | | | | | | |
| | Stage 1 | 0.9346 | 0.9850 | | 0.8214 | 0.9574 | | 0.8476 | |
| | Stage 2 | 0.9764 | 0.9746 | | 0.7825 | 0.9258 | 0.9783 | | |
| | Stage 3 | 0.9877 | 0.9843 | | | | 0.9867 | | |
| | Stage 4 | | | | | | | | |
| SYSTEM | Propulsion | 0.9568 | 0.9701 | | 0.8725 | 0.9290 | 0.9622 | 0.7355 | |
| | Guidance | 0.9830 | 0.9980 | | | 0.9929 | 0.9892 | | |
| | Flight Control | 0.9907 | 0.9851 | | | 0.9858 | 0.9946 | | |
| | Structure | 0.9989 | | | 0.9702 | | 0.9946 | | |
| | Electrical | 0.9815 | 0.9950 | | | 0.9929 | | | |
| | Seperation | 0.9969 | 0.9950 | | | 0.9858 | | | |
| | Other or (UK) | 0.9923 | | | | | | | |

| | Vehicle Name / Data Collection Period | Atlas A 57-58 | Atlas B 58-59 | Atlas C 58-59 | Atlas D 59-67 | Atlas E 60-66 | Atlas F 61-81 | Atlas SLV 67-83 | Atlas G 84-87 | Atlas H 83-87 | Atlas/Centaur 62-87 | Atlas: Combine 57-88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Success Ratio: Mean | 0.4219 | 0.5556 | 0.5833 | 0.8401 | 0.7428 | 0.8863 | 0.9445 | no failure | no failure | 0.9069 | 0.7863 |
| | 5% | 0.1827 | 0.3010 | 0.2642 | 0.8015 | 0.6454 | 0.8359 | 0.8736 | 0.8313 | 0.6313 | 0.8450 | 0.4781 |
| | 95% | 0.6977 | 0.7898 | 0.8565 | 0.8734 | 0.8240 | 0.9276 | 0.9852 | | | 0.9489 | 0.9953 |
| STAGE NO. | Stage 0 | | | | | | | | | | | |
| | Stage 1/2 | | | | | 0.8713 | 0.9573 | 0.9881 | | | 0.9814 | |
| | Stage 1 | | | | | 0.8523 | 0.9279 | 0.9719 | | | 0.9810 | |
| | Stage 2 | | | | | | | 0.9856 | | | 0.9420 | |
| | Stage 3 | | | | | | | | | | | |
| | Stage 4 | | | | | | | | | | | |
| SYSTEM | Propulsion | 0.8844 | 0.6667 | | | 0.8713 | 0.9212 | 0.9824 | | | 0.9535 | |
| | Guidance | | | | | 0.9571 | 0.9888 | | | | | |
| | Flight Control | 0.7686 | 0.8889 | | | 0.9428 | 0.9888 | 0.9824 | | | 0.9907 | |
| | Structure | 0.7686 | | | | 0.9857 | | | | | 0.9814 | |
| | Electrical | | | | | 0.9857 | | 0.9824 | | | 0.9907 | |
| | Seperation | | | | | | | 0.9824 | | | 0.9907 | |
| | Other or (UK) | | | | | | 0.9934 | | | | | |

| | Vehicle Name / Data Collection Period | Saturn "Family": Jupiter 56-58 | Saturn "Family": Juno 58-61 | Saturn "Family": Saturn I 62-65 | Saturn "Family": Saturn IB 66-75 | Saturn "Family": Saturn V 67-73 | Saturn "Family": Combine 56-75 | Scout "Family": Vanguard 57-59 | Scout "Family": Scout 60-88 | Scout "Family": Combine 57-88 | STS: Space Shuttle 81-88 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Success Ratio: Mean | 0.3811 | 0.4300 | no failure | no failure | 0.9822 | 0.7547 | 0.3388 | 0.9420 | 0.8404 | 0.9275 |
| | 5% | 0.1028 | 0.2135 | 0.7943 | 0.7743 | 0.8180 | 0.2852 | 0.1565 | 0.9023 | 0.1821 | 0.8147 |
| | 95% | 0.6879 | 0.6743 | | | 0.9997 | 0.9935 | 0.5723 | 0.9683 | 0.8744 | 0.9808 |
| STAGE NO. | Stage 0 | | | | | | | | | | |
| | Stage 1/2 | | | | | | | | | | |
| | Stage 1 | | 0.8575 | | | | | 0.8347 | 0.9917 | | 0.9275 |
| | Stage 2 | 0.5741 | 0.7009 | | | 0.9822 | | 0.5049 | 0.9875 | | |
| | Stage 3 | | 0.7829 | | | 0.9822 | | 0.8039 | 0.9746 | | |
| | Stage 4 | 0.6290 | 0.9378 | | | | | | 0.9870 | | |
| SYSTEM | Propulsion | 0.7870 | | | | | | 0.7521 | 0.9793 | | 0.9275 |
| | Guidance | | | | | | | 0.9174 | 0.9917 | | |
| | Flight Control | | | | | | | 0.8347 | 0.9917 | | |
| | Structure | | | | | | | | | | |
| | Electrical | | | | | | | | 0.9876 | | |
| | Seperation | 0.5741 | | | | | | | 0.9958 | | |
| | Other or (UK) | | | | | | | 0.8347 | 0.9958 | | |

## TABLE A.2a: RELIABILITY OF THE THOR/DELTA FAMILY

| Vehicle Name<br>Data Collection<br>Period | | Thor / Delta | | |
|---|---|---|---|---|
| | | Thor<br>57-83 | Delta<br>60-87 | Combine<br>57-87 |
| Success Ratio: Mean<br>5%<br>95% | | 0.8982<br>0.8750<br>0.9181 | 0.9402<br>0.9110<br>0.9615 | 0.9192<br>0.8789<br>0.9551 |
| STAGE NO. | Stage 0 | 0.9965 | 0.9950 | |
| | Stage 1/2 | | | |
| | Stage 1 | 0.9346 | 0.9850 | |
| | Stage 2 | 0.9764 | 0.9746 | |
| | Stage 3 | 0.9877 | 0.9843 | |
| | Stage 4 | | | |
| SYSTEM | Propulsion | 0.9568 | 0.9701 | |
| | Guidance | 0.9830 | 0.9950 | |
| | Flight Control | 0.9907 | 0.9851 | |
| | Structure | 0.9969 | | |
| | Electrical | 0.9815 | 0.9950 | |
| | Separation | 0.9969 | 0.9950 | |
| | Other or (UK) | 0.9923 | | |

# TABLE A.2b: RELIABILITY OF THE TITAN FAMILY

| | Vehicle Name Data Collection Period | Titan | | | | |
|---|---|---|---|---|---|---|
| | | Titan I 59-65 | Titan II 62-76 | Titan III 64-87 | Titan 34D 82-87 | Combine 59-87 |
| Success Ratio: | Mean | 0.6427 | 0.8864 | 0.9406 | 0.7355 | 0.8013 |
| | 5% | 0.5585 | 0.8323 | 0.9055 | 0.4978 | 0.6075 |
| | 95% | 0.7202 | 0.9272 | 0.9651 | 0.8990 | 0.9546 |
| STAGE NO. | Stage 0 | | | 0.9946 | 0.8678 | |
| | Stage 1/2 | | | | | |
| | Stage 1 | 0.8214 | 0.9574 | | 0.8476 | |
| | Stage 2 | 0.7825 | 0.9258 | 0.9783 | | |
| | Stage 3 | | | 0.9667 | | |
| | Stage 4 | | | | | |
| SYSTEM | Propulsion | 0.6725 | 0.9290 | 0.9622 | 0.7355 | |
| | Guidance | | 0.9929 | 0.9892 | | |
| | Flight Control | | 0.9858 | 0.9946 | | |
| | Structure | 0.9702 | | 0.9946 | | |
| | Electrical | | 0.9929 | | | |
| | Separation | | 0.9858 | | | |
| | Other or (UK) | | | | | |

## TABLE A.2c: RELIABILITY OF THE ATLAS FAMILY

| Vehicle Name / Data Collection Period | | Atlas | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Atlas A 57-58 | Atlas B 58-59 | Atlas C 58-59 | Atlas D 59-67 | Atlas E 60-88 | Atlas F 61-81 | Atlas SLV 67-83 | Atlas G 84-87 | Atlas H 83-87 | Atlas/ Centaur 62-87 | Combine 57-88 |
| Success Ratio: Mean | | 0.4219 | 0.5558 | 0.5833 | 0.8401 | 0.7426 | 0.8883 | 0.9445 | no failure | no failure | 0.9069 | 0.7883 |
| 5% | | 0.1827 | 0 3010 | 0.2642 | 0.8015 | 0.6454 | 0.8359 | 0.8736 | 0.6313 | 0.6313 | 0.8450 | 0.4761 |
| 95% | | 0.6977 | 0.7896 | 0.8585 | 0.8734 | 0.8240 | 0.9276 | 0.9652 | | | 0.9489 | 0.9953 |
| STAGE NO. | Stage 0 | | | | | | | | | | | |
| | Stage 1/2 | | | | | 0.8713 | 0.9573 | 0.9861 | | | 0.9814 | |
| | Stage 1 | | | | | 0.8523 | 0.9279 | 0.9719 | | | 0.9810 | |
| | Stage 2 | | | | | | | 0.9856 | | | 0.9420 | |
| | Stage 3 | | | | | | | | | | | |
| | Stage 4 | | | | | | | | | | | |
| SYSTEM | Propulsion | 0.8844 | 0.6667 | | | 0.8713 | 0.9212 | 0.9824 | | | 0.9535 | |
| | Guidance | | | | | 0.9571 | 0.9869 | | | | | |
| | Flight Control | 0.7688 | 0.8889 | | | 0.9428 | 0.9869 | 0.9824 | | | 0.9907 | |
| | Structure | 0.7688 | | | | 0.9857 | | | | | 0.9814 | |
| | Electrical | | | | | 0.9857 | | 0.9824 | | | 0.9907 | |
| | Separation | | | | | | | 0.9824 | | | 0.9907 | |
| | Other or (UK) | | | | | | 0.9934 | | | | | |

## TABLE A.2d: RELIABILITY OF THE SATURN FAMILY

| | Vehicle Name<br>Data Collection<br>Period | Saturn "Family" | | | | | |
|---|---|---|---|---|---|---|---|
| | | Jupiter<br>58-58 | Juno<br>58-61 | Saturn I<br>62-65 | Saturn IB<br>66-75 | Saturn V<br>67-73 | Combine<br>58-75 |
| | Success Ratio: Mean<br>5%<br>95% | 0.3611<br>0.1026<br>0.6879 | 0.4300<br>0.2135<br>0.6743 | no failure<br>0.7943 | no failure<br>0.7743 | 0.9822<br>0.8180<br>0.9997 | 0.7547<br>0.2652<br>0.9935 |
| STAGE NO. | Stage 0 | | | | | | |
| | Stage 1/2 | | | | | | |
| | Stage 1 | | 0.8575 | | | | |
| | Stage 2 | 0.5741 | 0.7009 | | | 0.9822 | |
| | Stage 3 | | 0.7629 | | | 0.9822 | |
| | Stage 4 | 0.6290 | 0.9378 | | | | |
| SYSTEM | Propulsion | 0.7870 | | | | | |
| | Guidance | | | | | | |
| | Flight Control | | | | | | |
| | Structure | | | | | | |
| | Electrical | | | | | | |
| | Separation | 0.5741 | | | | | |
| | Other or (UK) | | | | | | |

## TABLE A2e: RELIABILITY OF THE SCOUT FAMILY

| | Vehicle Name Data Collection Period | Scout "Family" | | |
|---|---|---|---|---|
| | | Vanguard 57-59 | Scout 60-88 | Combine 57-88 |
| | Success Ratio: Mean | 0.3388 | 0.9420 | 0.6404 |
| | 5% | 0.1555 | 0.9023 | 0.1821 |
| | 95% | 0.5723 | 0.9683 | 0.9744 |
| STAGE NO. | Stage 0 | | | |
| | Stage 1/2 | | | |
| | Stage 1 | 0.8347 | 0.9917 | |
| | Stage 2 | 0.5049 | 0.9875 | |
| | Stage 3 | 0.8039 | 0.9746 | |
| | Stage 4 | | 0.9870 | |
| SYSTEM | Propulsion | 0.7521 | 0.9793 | |
| | Guidance | 0.9174 | 0.9917 | |
| | Flight Control | 0.8347 | 0.9917 | |
| | Structure | | | |
| | Electrical | | 0.9876 | |
| | Separation | | 0.9959 | |
| | Other or (UK) | 0.8347 | 0.9959 | |

## TABLE A.2f: RELIABILITY OF THE SPACE SHUTTLE

| | | STS |
|---|---|---|
| Vehicle Name<br>Data Collection<br>Period | | Space Shuttle<br>81-88 |
| Success<br>Ratio: Mean<br>5%<br>95% | | 0.9275<br>0.8147<br>0.9806 |
| STAGE NO. | Stage 0 | |
| | Stage 1/2 | |
| | Stage 1 | 0.9275 |
| | Stage 2 | |
| | Stage 3 | |
| | Stage 4 | |
| SYSTEM | Propulsion | 0.9275 |
| | Guidance | |
| | Flight Control | |
| | Structure | |
| | Electrical | |
| | Separation | |
| | Other or (UK) | |

## 1.0 EXISTING METHODOLOGIES

For the purposes of this report, the following existing methodologies will be briefly discussed.

- Binomial
- Polynomial Curve Fitting
- Bayesian
- D. Lloyd's Method

### 1.1 The Binomial Method

The "traditional," or classical, approach to reliability demonstration in a go/no-go type environment is the Binomial distribution shown below. In addition to the obvious constraints of the assumptions listed below, it is interesting to note, for example, that it would require 45 launches with no failures to demonstrate 0.95 reliability at 90% confidence. Since trials are assumed to be independent, the growth effect (a type of dependency) cannot be evaluated.

Stated mathematically the Binomial Distribution is as follows:

$$\sum_{X=S}^{N} \binom{N}{N-X} R^{X} (1-R)^{N-X} = 1 - C, \quad \text{if } N \leq S \leq 0$$

where;

S = number of successful start tests
N = number of trials
R = reliability
C = confidence level

where it is assumed that

- Trials or tests are independent
- Each trial results in success or failure
- The reliability (probability of success) of each system is the same on each trial
- The number of tests is fixed in advance of the demonstration test

### 1.2 Polynomial Curve Fitting

Polynomial trends are of the form

$$Y = A + BX + CX^2 + DX^3 + \ldots JX^k$$

The straight line is a special case having only the first two terms on the right hand side of the equation. Generally speaking, it is unwise to fit a high-degree polynomial to the data because of the possibility of mixing trend and cycle. The polynomial can be forced to fit data quite closely by just adding enough terms. This, however, does not contribute any information about trend. In fact, 1 degree of freedom for error is lost for every parameter that is estimated from data. Thus, if there are n observations and n degrees of freedom are lost in fitting a polynomial of degree n-1 item, there are 0 degrees of freedom left for error!

## 1.3 Bayesian Analysis

For the purposes of this report, Bayesian analysis can be divided into two categories:

1. Reduction of the number of tests or flights to demonstrate that a given level of reliability has been achieved.

2. The Beta-Binomial Model

If it is desired to reduce the numbers of tests or flights required to demonstrate a given level of reliability, then Bayesian analysis can be useful. If the following equation, taken from reference 1, is solved for n at R=0.95, r=0, P=0.50 and C=90% confidence is desired, then it can be concluded that only 14 launches would be required.

$$C = \frac{1}{1 + \dfrac{(1-P)(1-R)^2 \int_0^R p^{n-r+1} q^r \, dp}{(P)(R)^2 \int_R^1 p^{n-r} q^{r+1} \, dp}}$$

where;

n = number of launches
r = number of failures
R = reliability
C = confidence level
P = Bayesian Prior

The Beta-Binomial Bayesian model is used for Bayesian estimation when information is available about components of similar design and application. In this model, several similar components are treated as a single class. The probability p of each component in the class is assumed to be constant, but will have different values from component to component. If the Binomial distribution is used to obtain the probability of K failures in n trials, then the conjugate distribution g(p) for the class is the Beta distribution. This model weights the reliability growth effect and can be applied to forecast the reliabilities of launch vehicles. The detailed theoretica' analysis can be found in reference 2. The disadvantage of this model is that it is very difficult to separate the total sample data into several similar components unless there is detailed engineering analysis concerning each failure mode during the different periods of launch vehicle development history.

Bayesian approaches are highly sensitive to the prior distributions used. If no meaningful estimate of the prior probability of success can be made, none of the above conclusions apply. Particularly, one must be wary of consistent optimism or pessimism when records of success do not support the prior probabilities.

## 1.4 D. Lloyd's Method

In Lloyd's model, the rationale is that when engineering corrective action for a failure is implemented, the probability of recurrence of that failure is reduced; therefore, such failures should not be carried as

full failures in subsequent reliability estimates. The failure value for each failure model is assumed to be

$$f = 1 - (1 - \gamma)^{1/n}$$

where $\gamma$ is the confidence level and n is the number of successful tests after corrective action.

Based on a detailed engineering analysis for each failure mode, the result of each failure for each failure mode can be obtained by solving the above equation. The final result of the reliability estimation is $R = 1 - \Sigma f/N$ where $\Sigma f$ is the cumulative failure number of all failure modes and N = the test number.

This model weights the growth effect and can be extended to forecast the reliability, the failure mode and the launch number at which the failure mode occured as well as the launch number at which it was corrected. The confidence level $\gamma$ is directly related to the final results and requires subjective judgement as to what value is to be used.

## 2.0 A NEW STATISTICAL MODEL

The developmental history of any launch vehicle can be considered as two time periods - the early testing period and the performance period. Generally, during the early testing period the unreliability of a launch vehicle is high and unstable. After a "failure, analysis, and fix" process, in conjunction with technical and design improvements, the unreliability of a launch vehicle decreases and stabilizes in the performance period.

A statistical model which weights the reliabilities of these two periods has been developed. The detailed descriptions of the materials for reliability analysis of vehicles, stages, systems, and engines (or motors) are introduced in the following sections.

### 2.1 Estimation of Launch Vechicle Reliability

The easiest way to estimate the average unreliability of a launch vehicle is:

$$U_e = F/L \tag{1}$$

where $U_e$ is the estimated average unreliability, and F and L are the cumulative failure and launch numbers.

As was mentioned before, the reliability growth effect must be considered to get a more realistic estimation of the unreliability. In the present model, the average unreliability is defined as

$$U = U_e - \Delta U \tag{2}$$

where $\Delta U$ is the change in reliability caused by reliability growth and can be explained as

$$\Delta U = \Delta F/L$$

or

$$\Delta F = \Delta U \cdot L \tag{3}$$

where $\Delta F$ is the cumulative failure correction number.

Averaging both sides of equation (3) results in

$$\overline{\Delta F} = \Delta U \cdot \frac{L}{2}$$

or

$$\Delta U = \frac{2}{L} \cdot \overline{\Delta F} \tag{4}$$

Substitute equation (1) and equation (4) into equation (2)

$$U = \frac{F}{L} - \frac{2}{L} \cdot \overline{\Delta F} \tag{5}$$

The estimation of the unreliability of the launch vehicle at the $n^{th}$ launch can then be approximated as

$$U_n = \frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N}\left(F_i - \frac{F_n}{L_n} \cdot L_i\right)}{N} \tag{6}$$

where $L_i$ is the $i^{th}$ launch number, and $F_i$ is the cumulative failure number at the $i^{th}$ launch.

The reliability $R_n$ at the $n^{th}$ launch is

$$R_n = 1 - U_n = 1 - \left[\frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N}\left(F_i - \frac{F_n}{L_n} \cdot L_i\right)}{N}\right] \tag{7}$$

The concepts of confidence levels based on the value of average reliability from equation (7) are now illustrated as the following.

Let N be the launch number, then $X = N \cdot R_n$ is the success number

5th confidence -

$$R_{005} = \frac{x}{x + (n - x + 1)\, F_{095}(2n - 2x + 2,\ 2x)} \tag{8}$$

95th confidence -

$$R_{095} = \frac{(x+1)\, F_{095}(2x+2, 2n-2x)}{(n-x) + (x+1)\, F_{095}(2x+2,\ 2n-2x)} \tag{9}$$

where $F_r(n_1, n_2)$ is the 100 $r^{th}$ percentile of F-distribution with $n_1$ numerator and $n_2$ denominator degrees of freedom.

This completes the formulation of the launch vehicle reliability calculations. The example which applies this model is given in section 5.

## 2.2 Estimation of Stage Reliability

The basic method of estimating the stage reliability of a launch vehicle in the present study is based on the following assumptions:

1. The failure of the launch vehicle must occur in one of its stages.

2. The starting operation time for each stage is followed by the order of stage number. In other words, the first stage should begin operating before the second stage.

The following formulation has been developed to perform the reliability estimation for the $i^{th}$ stage

$$R_{si} = 1 - \frac{F_{si} \cdot U_v}{F_v - \left( \sum_{j=1, j\leq i-1}^{i-1} F_{si} \right) \cdot U_v} \tag{10}$$

where $R_{si}$ is the reliability of the $i^{th}$ stage, $F_{si}$ is the cumulative failure number of the $i^{th}$ stage, $F_v$ is the cumulative failure number of the launch vehicle, $U_v$ is the unreliability of the launch vehicle from equation (6).

For example, the reliability for

First stage: $R_{s1} = 1 - \dfrac{F_{s1} \cdot U_v}{F_v}$

Second stage: $R_{s2} = 1 - \dfrac{F_{s2} \cdot U_v}{F_v - F_{s1} \cdot U_v}$

Third stage: $R_{s3} = 1 - \dfrac{F_{s3} \cdot U_v}{F_v - (F_{s1} + F_{s2}) \cdot U_v}$

Since the value of $U_v$ in equation (10) has been weighted, the estimation of reliability for each stage $R_i$ is also a weighted average.

## 2.3 Estimation of System Reliability

The basic assumption for the method of estimating system relaibility in the present study is that the failure of the launch vehicle must occur in one of its systems.

The average reliability of each system of the launch vehicle can be formulated as

$$R_{sys\,i} = 1 - U_v \cdot F_{sys\,i} / F_v \tag{11}$$

where $R_{sysi}$ is the reliability of the $i^{th}$ system, $F_{sysi}$ is the cumulative failure number of the $i^{th}$ system, $U_v$ is the unreliability of the launch vehicle, $F_v$ is the cumulative failure number of the launch vehicle.

## 2.4 Estimation of Engine (or Motor) Reliability

The basic assumption of the method for estimating engine (or motor) reliability is if any of the engines (or motors) in a stage fails, then the entire stage has failed. Since the failure of a stage can be caused by either engine (or motor) failure or other failures, the cumulative failure number of engine (or motor) in this stage needs to be known. The model for estimating engine (or motor) reliability is described as

$$R_{ei} = (1 - U_{si} \cdot F_{ei} / F_{si})^{1/N_{ei}}$$

where

$R_{ei}$ is the reliability of the engine (or motor) in the $i^{th}$ stage.

$U_{si}$ is the unreliability of the $i^{th}$ stage which can be obtained by $1-R_{si}$ from equation (10).

$F_{ei}$ is the engine (or motor) cumulative failure number in the $i^{th}$ stage.

$F_{si}$ is the cumulative failure number of the $i^{th}$ stage.

$N_{ei}$ is the number of engines (or motors) in the $i^{th}$ stage.

## 3.0 DATA COLLECTION

Based on the analysis of section 2, the following table for data collection of each launch vehicle was developed.

Vehicle Name ____________________

Data Collection from _________ Yr to __________ Yr

Total Launch Number _________________

Total Failure Number _________________

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Descrptn | Engine or Failure Y/N |
|---|---|---|---|---|---|---|
| | | | | | | |

Table A.3

In this table,

<u>Date:</u> the date when the launch vehicle failed
<u>Failure Launch:</u> the launch number at which the launch failed
<u>Success Run:</u> the number of successful launches between two failures
<u>Failure Stage:</u> failure stage number
<u>Failure System:</u> one of the following systems failed: propulsion, separation, flight control, structure, electrical, guidance, etc...
<u>Failure Description:</u> failure mode
<u>Engine or Motor Failure Y/N:</u> Y = engine or motor failure; N = no engine or motor failure.

This table template was then applied to the history of all US Launch Vehicle Families according to given cut-off dates. The cut-off dates and the resulting historical tabulations are given in the supplement to this appendix.

## 4.0 ALGORITHM

The general solution procedures of launch vehicle reliability analysis can be described by the following steps.

1. Use Table A.3 to collect the data for each launch vehicle.

2. From the date of "Failure Launch" listed in Table A.3, the launch vehicle reliability can be estimated by applying equation (7) in section 2.1. The corresponding 95th and 5th confidence levels can be obtained by solving equations (8) and (9) in section 2.1.

3. From the data of "Failure Stage" listed in Table A.3 and the launch reliability obtained in step 2, the reliability of each stage of the launch vehicle can be calculated by using equation (10) in section 2.2.

4. The date of "Failure System" together with the results of step 2 provide the information to obtain the reliability of each system in the launch vehicle by applying equation (11) in section 2.3.

5. From the data of "Engine (or Motor) Failure Y/N" listed in Table A.3 and the result of step 3, the reliabilities of each engine (or motor) can be obtained by solving equation (12).

## 5.0 EXAMPLE

Consider the "Atlas/Centaur" as an example. The general information about the "Atlas/Centaur" is illustrated in the following figure which is taken from the report "Hazard Analysis of Commercial Space Transportation", Volume I, May 1988, published by the U.S. Department of Transportation.

Following the solution procedures described in section 4:

1. Table A.4 lists all the failure data on the "Atlas/Centaur", The data collection period is from 1962 to 1987. The launch number of the "Atlas/Centaur" during this period is 67, and the corresponding failure number is 11. In this example, the failure data was collected from the "Launch Vehicle Failure History Data Base," which was compiled by Cindy Thatcher Clague of the Aerospace Corporation (reference 4).

The March 26, 1987 failure, shown in Table A.4, which was caused by a lightning strike is considered as an externally caused failure. This failure is eliminated in the present reliability analysis otherwise all failures are included.

2. Based on the data in Table A.4, we used equation (7) in Section 2.1 to estimate the launch vehicle reliability. The estimation of the reliability for n=67 is

$$R_n = 0.9069$$

The corresponding 95th and 5th confidence levels, obtained by solving equations (8) and (9), are

$$R_{0.05} = 0.8450$$
$$R_{0.95} = 0.9489$$

3. From the "Stage Failure" data in Table A.4

The first stage is stage 1/2 and has the failure number $F_{1/2} = 2$.
The second stage is stage 1 and has the failure number $F_1 = 2$.
The third stage is stage 2 and has the failure number $F_2 = 6$.

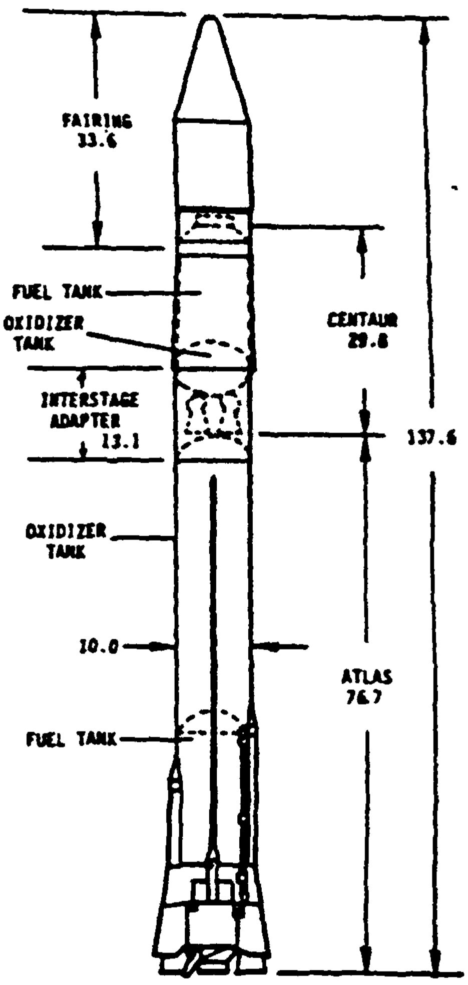
The reliability of each stage can be obtained by solving equation (10). In this example, the unreliability of the vehicle is $U_v = 1 - R_v = 0.0931$, and the cumulative failure number of the vehicle is $F_v = 10$. Substituting these values into equation (10), we get

$R_{s1} = 0.9814$ for stage 1/2.
$R_{s2} = 0.9810$ for stage 1.
$R_{s3} = 0.9420$ for stage 2.

4. From the "System Failure" data in Table A.4

The failure number of the propulsion is 5.
The failure number of the structure is 2.
The failure number of the separation is 1.
The failure number of the flight control is 1.
The failure number of the electrical is 1.

## General Dynamics




## General Stage Data
## Atlas Centaur Launch Vehicle

| | Stage 1/2 | Stage 1 | Stage 2 |
|---|---|---|---|
| **Stage Data** | | | |
| Designation | Atlas G | | Centaur D-1A |
| Stage Mass, klbm | 320.675 | | 38.777 |
| Usable Propellant, klbm | 300.632 | | 29.734 |
| Stage Length, ft | 76.7 | | 29.8 |
| Stage Diameter, ft | 10 | | 10 |
| Number of Engines | 2 | 1 | 2 |
| **Guidance Data** | | | |
| Manufacturer | | | Honeywell |
| Type | | | Four Gimbal Inertial |
| **Engine Data** | | | |
| Manufacturer | Rocketdyne | Rocketdyne | Pratt and Whitney |
| Designation | YLR-89-NA-7 | YLR-105-NA-7 | RL-10A-3-3A |
| Number of Starts Possible | 1 | 1 | 2 |
| Fuel | RP-1 | RP-1 | $LN_2$ |
| Oxidizer | LOX | LOX | LOX |
| Mixture Ratio, O/F | 2.25 | 2.22 | 5.0 |
| Average Thrust per Engine, lbf | | | |
| Sea Level | 180,750 | 60,500 | — |
| Vacuum | — | — | 16,500 |
| Average Chamber Pressure, psia | 650 | 733 | 474 |
| Specific Impulse, sec | | | |
| Sea Level | 259 | 220 | |
| Vacuum | 292 | 312 | 446.4 |
| Total Burn Time, sec | 153 | 283 | 404 |
| Nozzle Expansion Ratio | 8 | 25 | 61 |
| Nozzle Exit Area, $ft^2$ | 11.24 | 11.56 | 8.22 |
| Engine Cant Angle, deg | 0 | 0 | 0 |
| Thrust Vector Control | Gimballed Engines and Verniers | | Gimballed Engine |

Figure A.1. Atlas/Centaur launch vehicle configuration and data.

## TABLE A.4: FAILURE HISTORY DATA OF ATLAS/CENTAUR

**Vehicle Name:** Atlas/Centaur
**Data Collection from:** 62 to 87
**Total Launch Number:** 67
**Total Failure Number:** 11

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 05/08/62 | 1 | 0 | 2 | Structure | Centaur upper stage structure failure | N |
| 06/30/64 | 3 | 1 | 2 | Propulsion | Centaur hydraulic failure, Loss of $C_2$ hydraulic power | N |
| 03/02/65 | 5 | 1 | 1/2 | Propulsion | Loss of Atlas thrust during liftoff, due to fuel starvation of booster engines stemming from closure of fuel prevelue | Y |
| 04/07/66 | 7 | 1 | 2 | Propulsion | Centaur restart sequence failure, engine ignition occurred but not sustained due to fuel deplation | N |
| 08/10/68 | 16 | 8 | 2 | Propulsion | Failure of boost pump $H_2O_2$ supply system centaur didn't achieve its second main engine start | N |
| 11/30/70 | 21 | 4 | 1 | Separation | Nose fairing failed to jettison properly | N |
| 05/08/71 | 23 | 1 | 2 | Flight Control | Centaur pitch control lost | N |
| 02/20/75 | 34 | 10 | 1 | Electrical | Atlas booster section electrical disconnect failed during booster jettison | N |
| 09/29/77 | 42 | 7 | 1/2 | Propulsion | Atlas booster engine hot gas leak failed mission | Y |
| 06/09/84 | 62 | 19 | 2 | Propulsion | Failure occurred at A/C Separation a liquid oxygen tank crack | N |
| 03/26/87 | 67 | 4 | --- | other | Lightning strike failed mission | N |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

By solving equation (11), the reliability of each system can be obtained

$$R_{propulsion} = 0.9535$$
$$R_{structure} = 0.9814$$
$$R_{separation} = 0.9907$$
$$R_{flight\ control} = 0.9907$$
$$R_{electrical} = 0.9907$$

5. There are two engines (YLR-89-NA-7) in stage 1/2, one engine (YLR-105-NA-7) in stage 1, and two engines (RL-10A-3-3A) in stage 2. From Table A.4, the failure number of engine YLR-89-NA-7 is 2. The failure number of engine YLR-105-NA-7 is 1, and the failure number of engine RL-10A-3-3A is 0. By solving equation (12) together with results of stage reliabilities, the reliabilities of each engine can be obtained.

$$R_{YLR\text{-}89\text{-}NA\text{-}7} = 0.9907$$
$$R_{YYLR\text{-}105\text{-}NA\text{-}7} = 0.9905$$
$$R_{RL\text{-}10A\text{-}3\text{-}3A} = \text{No Failure}$$

The results of the reliability analysis for the "Atlas/Centaur" are summarized as

| ATLAS/CENTAUR | RELIABILITY |
|---|---|
| **Vehicle** | |
| Mean | 0.9069 |
| 5% | 0.8450 |
| 95% | 0.9489 |
| **Stages** | |
| Stage 1/2 | 0.9814 |
| Stage 1 | 0.9810 |
| Stage 2 | 0.9420 |
| **System** | |
| Propulsion | 0.9535 |
| Structure | 0.9814 |
| Separation | 0.9907 |
| Flight Control | 0.9907 |
| Electrical | 0.9907 |
| **Engines** | |
| YLR-89-NA-7 | 0.9907 |
| YLR-105-NA-7 | 0.9905 |
| RL-10A-3-3A | No Failure |

The reliability estimation of "Atlas/Centaur" based on equation (7) at each launch is described in the following figure, A.2.

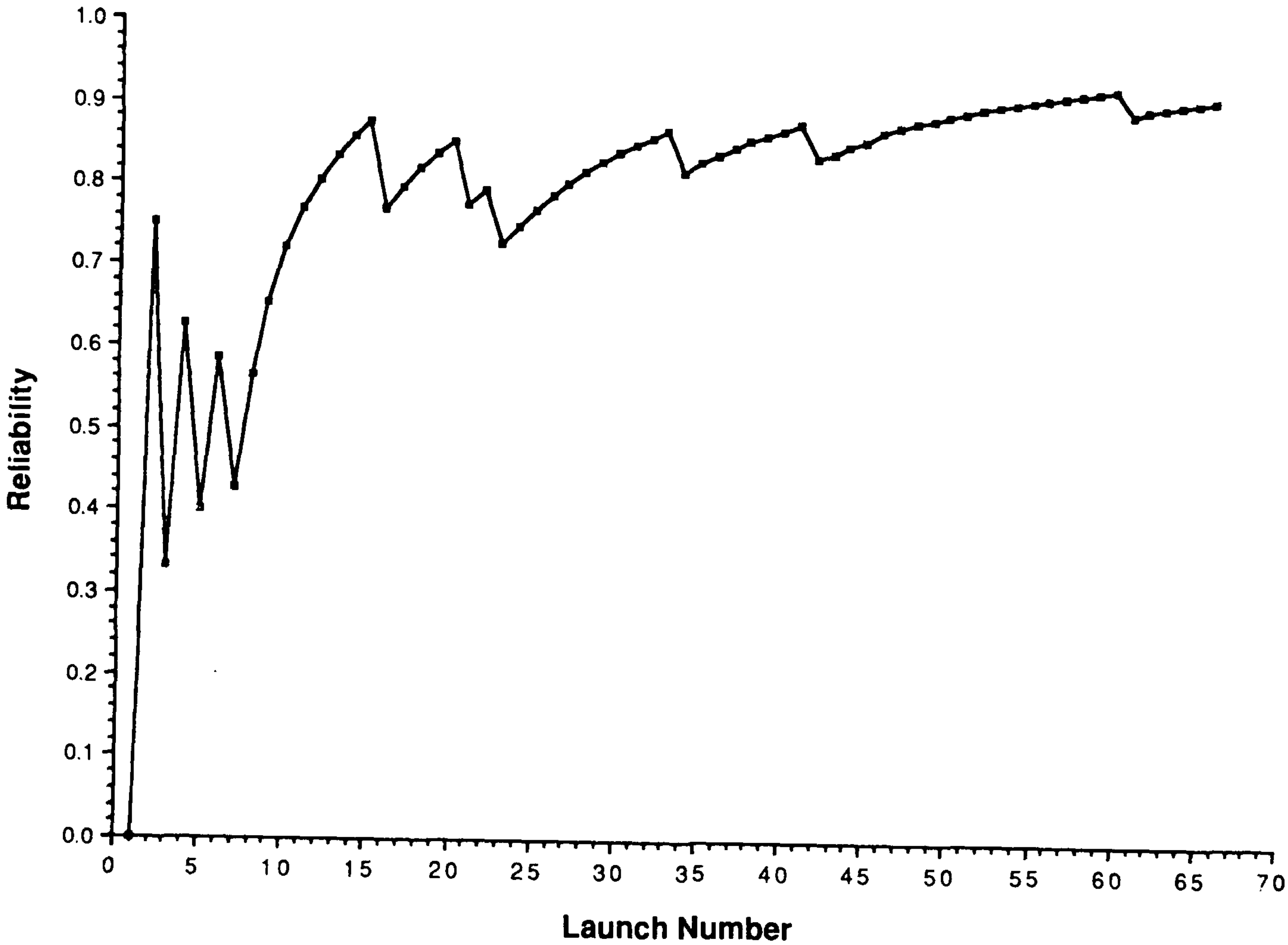



Figure A.2. Reliability estimation of Atlas/Centaur.

## 6.0 RESULTS

The statistical model (section 2) and the data collection method (section 3) following the solution procedures (section 4) have been applied to twenty-four U.S. launch vehicles. The results are listed in Table A.5.

In Table A.5, launch vehicles are separated into six groups based on their developmental histories. The results of the "Combine" in Table A.5 are the reliability estimates for each group. The following formulations, based on Bayesian reliability analysis, have been applied to perform the calculation for each group.

$$\mu = \frac{1}{N}\sum_{i=1}^{N} R_i$$

where N is the vehicle number in the group, $R_i$ is the reliability of the $i^{th}$ vehicle, $\mu$ is the mean reliability of the group.

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(R_i - \mu)^2$$

where $\sigma^2$ is the variance.

Let

$$a = \frac{\mu^2}{\sigma^2}(1-\mu) - \mu$$

$$b = \frac{\mu}{\sigma^2}(1-\mu) + \mu - 1$$

Then the mean of the group is

$$\mu = a/(a+b)$$

The 5% confidence level is

$$R_{05} = \frac{a}{a + b \cdot F_{095}(2b, 2a)}$$

The 95% confidence level is

$$R_{095} = \frac{a \cdot F_{095}(2a, 2b)}{b + a \cdot F_{095}(2a, 2b)}$$

The reliability estimations for each engine of the launch vehicles are not listed in Table A.5. They are partially listed in the matrices which are for engine reliability analysis.

# TABLE A.5: RELIABILITY COMPARISON OF U.S. LAUNCH VEHICLE FAMILIES

| | Vehicle Name / Data Collection Period | Thor / Delta: Thor 57-83 | Thor / Delta: Delta 60-87 | Thor / Delta: Combine 57-87 | Titan: Titan I 59-65 | Titan: Titan II 62-76 | Titan: Titan III 64-87 | Titan: Titan 34D 82-87 | Titan: Combine 59-87 | Atlas: Atlas A 57-58 | Atlas: Atlas B 58-59 | Atlas: Atlas C 58-59 | Atlas: Atlas D 59-67 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Success Ratio: Mean | 0.8982 | 0.9402 | 0.9192 | 0.6427 | 0.8884 | 0.9408 | 0.7355 | 0.8013 | 0.4219 | 0.5556 | 0.5833 | 0.8401 |
| | 5% | 0.8730 | 0.9110 | 0.8789 | 0.5585 | 0.8323 | 0.9056 | 0.4978 | 0.8075 | 0.1827 | 0.3010 | 0.2642 | 0.8015 |
| | 95% | 0.9181 | 0.9615 | 0.9551 | 0.7202 | 0.9272 | 0.9651 | 0.8990 | 0.9546 | 0.8977 | 0.7898 | 0.8565 | 0.8734 |
| STAGE NO. | Stage 0 | 0.9965 | 0.9950 | | | | 0.9946 | 0.8678 | | | | | |
| STAGE NO. | Stage 1/2 | | | | | | | | | | | | |
| STAGE NO. | Stage 1 | 0.9348 | 0.9850 | | 0.8214 | 0.9574 | | 0.8478 | | | | | |
| STAGE NO. | Stage 2 | 0.9784 | 0.9746 | | 0.7825 | 0.9258 | 0.9783 | | | | | | |
| STAGE NO. | Stage 3 | 0.9877 | 0.9843 | | | | 0.9867 | | | | | | |
| STAGE NO. | Stage 4 | | | | | | | | | | | | |
| SYSTEM | Propulsion | 0.9588 | 0.9701 | | 0.8725 | 0.9290 | 0.9822 | 0.7355 | | 0.8844 | 0.6687 | | |
| SYSTEM | Guidance | 0.9830 | 0.9850 | | | 0.9929 | 0.9892 | | | | | | |
| SYSTEM | Flight Control | 0.9907 | 0.9851 | | | 0.9858 | 0.9946 | | | 0.7888 | 0.8889 | | |
| SYSTEM | Structure | 0.9989 | | | 0.9702 | | 0.9946 | | | 0.7888 | | | |
| SYSTEM | Electrical | 0.9815 | 0.9850 | | | 0.9929 | | | | | | | |
| SYSTEM | Separation | 0.9989 | 0.9950 | | | 0.9858 | | | | | | | |
| SYSTEM | Other or (UK) | 0.9923 | | | | | | | | | | | |

| | Vehicle Name / Data Collection Period | Atlas: Atlas E 60-66 | Atlas: Atlas F 61-81 | Atlas: Atlas SLV 67-83 | Atlas: Atlas G 84-87 | Atlas: Atlas H 83-87 | Atlas: Atlas/Centaur 62-87 | Atlas: Combine 57-88 | Saturn "Family": Jupiter 58-58 | Saturn "Family": Juno 58-61 | Saturn "Family": Saturn I 62-65 | Saturn "Family": Saturn IB 66-75 | Saturn "Family": Saturn V 67-73 | Saturn "Family": Combine 58-75 | Scout "Family": Vanguard 57-59 | Scout "Family": Scout 60-88 | Scout "Family": Combine 57-88 | STS: Space Shuttle 81 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Success Ratio: Mean | 0.7426 | 0.8863 | 0.9445 | no failure | no failure | 0.9089 | 0.7863 | 0.3611 | 0.4300 | no failure | no failure | 0.9822 | 0.7547 | 0.3366 | 0.9420 | 0.6404 | 0.9275 |
| | 5% | 0.6454 | 0.8359 | 0.8736 | 0.6313 | 0.6313 | 0.8450 | 0.4761 | 0.1026 | 0.2136 | 0.7943 | 0.7743 | 0.8180 | 0.2652 | 0.1556 | 0.9023 | 0.1821 | 0.8147 |
| | 95% | 0.8240 | 0.9276 | 0.9652 | | | 0.9489 | 0.9953 | 0.8879 | 0.6743 | | | 0.9997 | 0.9835 | 0.5723 | 0.9683 | 0.9744 | 0.9806 |
| STAGE NO. | Stage 0 | | | | | | | | | | | | | | | | | |
| STAGE NO. | Stage 1/2 | 0.8713 | 0.9573 | 0.9861 | | | 0.9814 | | | | | | | | | | | |
| STAGE NO. | Stage 1 | 0.8523 | 0.9279 | 0.9719 | | | 0.9810 | | | 0.8575 | | | | | 0.8347 | 0.9917 | | 0.9275 |
| STAGE NO. | Stage 2 | | | 0.9856 | | | 0.9420 | | 0.5741 | 0.7009 | | | 0.9822 | | 0.5049 | 0.9875 | | |
| STAGE NO. | Stage 3 | | | | | | | | | 0.7829 | | | 0.9822 | | 0.8039 | 0.9746 | | |
| STAGE NO. | Stage 4 | | | | | | | | 0.6290 | 0.9378 | | | | | | 0.9870 | | |
| SYSTEM | Propulsion | 0.8713 | 0.9212 | 0.9824 | | | 0.9535 | | 0.7870 | | | | | | 0.7521 | 0.9743 | | 0.9275 |
| SYSTEM | Guidance | 0.9571 | 0.9889 | | | | | | | | | | | | 0.9174 | 0.9917 | | |
| SYSTEM | Flight Control | 0.9428 | 0.9889 | 0.9824 | | | 0.9907 | | | | | | | | 0.8347 | 0.9917 | | |
| SYSTEM | Structure | 0.9857 | | | | | 0.9814 | | | | | | | | | | | |
| SYSTEM | Electrical | 0.9857 | | 0.9824 | | | 0.9907 | | | | | | | | | 0.9878 | | |
| SYSTEM | Separation | | | 0.9824 | | | 0.9907 | | 0.8741 | | | | | | | 0.9959 | | |
| SYSTEM | Other or (UK) | | 0.9934 | | | | | | | | | | | | 0.8347 | 0.9959 | | |

# 7.0 CONCLUSIONS

A new model has been developed which has the following advantages:

1. This model weights the reliability growth effect. Since the reliability of a launch vehicle can be estimated from each past launch, the extension of this model should be able to predict the future reliability of the launch vehicle.

2. The formulations of the model are simple and easy to apply. A computer program is being developed for future applications.

3. The results of the calculations are only dependent on the data collection.

4. The reliability estimations of vehicles, stages, systems, and engines are separated, which reduces the restrictions to the data collection.

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# Appendix A.4

## History of US Launch Vehicles

# Cut-off dates for launch vehicle reliability data

| Launch vehicle | Cut-off date | Failure No. | Launch No. |
|---|---|---|---|
| **Thor/Delta** | | | |
| Thor | 01/25/57 - 08/05/83 | 66 | 369 |
| Delta | 05/13/60 - 03/20/87 | 12 | 181 |
| **Titan** | | | |
| Titan I | 02/06/59 - 03/05/65 | 24 | 68 |
| Titan II | 03/16/62 - 06/27/76 | 16 | 94 |
| Titan III | 09/01/64 - 02/11/87 | 11 | 137 |
| Titan 34D | 10/30/82 - 11/28/87 | 2 | 11 |
| **Atlas** | | | |
| Atlas A | 06/11/57 - 06/03/58 | 5 | 8 |
| Atlas B | 07/19/58 - 02/04/59 | 4 | 9 |
| Atlas C | 12/23/58 - 08/24/59 | 3 | 6 |
| Atlas D | 04/14/59 - 11/07/67 | 42 | 197 |
| Atlas E | 10/11/60 - 02/03/88 | 18 | 49 |
| Atlas F | 08/08/61 - 06/23/81 | 17 | 96 |
| Atlas SLV | 02/02/67 - 05/19/83 | 4 | 73 |
| Atlas G | 06/09/84 - 03/26/87 | 0 | 5 |
| Atlas H | 02/09/83 - 05/15/87 | 0 | 5 |
| Atlas/Centaur | 05/08/62 - 03/26/87 | 10 | 67 |
| **Saturn "Family"** | | | |
| Jupiter | 07/26/58 - 10/23/58 | 3 | 6 |
| Juno | 12/06/58 - 05/24/61 | 5 | 10 |
| Saturn I | 10/27/62 - 07/30/65 | 0 | 10 |
| Saturn IB | 02/26/66 - 07/15/75 | 0 | 9 |
| Saturn V | 11/09/67 - 05/14/73 | 1 | 13 |
| **Scout "Family"** | | | |
| Vanguard | 12/06/57 - 09/18/59 | 8 | 11 |
| Scout | 07/01/60 - 03/25/88 | 14 | 110 |
| **STS** | | | |
| Space Shuttle | 04/12/81 - 09/29/88 | 1 | 26 |

**Vehicle Name:** Thor
**Data Collection from:** 57 to 83
**Total Launch Number:** 369
**Total Failure Number:** 66

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 01/25/57 | 1 | 0 | 1 | Propulsion | Missile fell back on launcher, oxygen start tank fill and check valve malfunction | Y |
| 04/19/57 | 2 | 0 | 1 | Human | Erroneously destroyed by RSU | N |
| 05/21/57 | 3 | 0 | 2 | Structure | Fuel tank ruptured | N |
| 08/30/57 | 4 | 0 | 1 | Propulsion | Propellant valve pneumatic line failure | Y |
| 10/03/57 | 6 | 1 | 1 | Electrical | Microswitch failure in MFV delayed signal to gas generator valve opening | N |
| 10/11/57 | 7 | 0 | 1 | Propulsion | Possible turbopump failure | Y |
| 12/07/57 | 9 | 1 | 1 | Electrical | Electrical systems malfunction, no main engine cutoff | N |
| 01/28/58 | 11 | 1 | 1 | Guidance | Excessive trajectory dispersion after 95 sec. terminated by RSO | N |
| 02/28/58 | 12 | 0 | 1 | Propulsion | Premature shutdown, failure of gas generator LRRP or liquid ox line | Y |
| 04/19/58 | 13 | 0 | 1 | Propulsion | Fell back on launcher due to fuel system malfunction | Y |
| 04/23/58 | 14 | 0 | 1 | Propulsion | Turbopump failure | Y |
| 07/13/58 | 18 | 3 | 1 | Electrical | Main engine cutoff failed to get through circuit problem | N |
| 07/26/58 | 20 | 1 | 1 | Structure | Pneumatic line failure caused MLV closure missile broke up due to aerodynamic forces | N |
| 08/17/58 | 22 | 1 | 1 | Propulsion | First stage malfunction, Turbopump failure | Y |
| 11/05/58 | 24 | 1 | 1 | Guidance | Autopilot malfunction | N |

**Vehicle Name:** Thor
**Data Collection from:** 57 to 83
**Total Launch Number:** 369
**Total Failure Number:** 66

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 11/08/58 | 25 | 0 | 3 | Propulsion | 3rd stage failed to ignite | Y |
| 12/05/58 | 27 | 1 | 1 | Propulsion | Liquid oxygen tank pressurization malfunction | N |
| 12/30/58 | 30 | 2 | 1 | Guidance | Guidance malfunction at liftoff | N |
| 01/21/59 | 31 | 0 | 1 | Propulsion | Exploded on pad. A malfunction during countdown | N |
| 01/23/59 | 32 | 0 | 2 | Electrical | Electrical malfunction prevented cutoff and 2nd stage Ignition | N |
| 01/30/59 | 33 | 0 | 1 | Propulsion | Liquid oxygen tank pressurization problem | N |
| 06/03/59 | 47 | 14 | 3 | Propulsion | Premature engine burnout due to fuel exhaustion, Insufficient velocity was gained for orbital attainment | Y |
| 06/16/59 | 49 | 1 | 1 | Guidance | Autopilot did not program possibly liftoff switch didnot extract | N |
| 06/25/59 | 51 | 1 | 2 | Electrical | A diode failure in the D-timer brake circuit caused the Agena engine to burn to fuel exhaustion | N |
| 06/29/59 | 52 | 0 | 1 | Electrical | Electrical malfunction R/V did not separate retro-rockets did not fine | N |
| 07/21/59 | 53 | 0 | 1 | Flight Control | Flight controller did not program; Launcher arm did not extract liftoff pin | N |
| 08/14/59 | 60 | 6 | 1 | Propulsion | Fuel depletion, fuel underload, leak or engine miscalibration | Y |
| 09/17/59 | 65 | 4 | 2 | Separation | 2nd stage retro device failed, 3rd stage did not ignite | N |
| 12/01/59 | 77 | 11 | 1 | Propulsion | Main engine cutoff occurred 6 sec. early. Possibly main liquid oxygen valve closed prematurely | Y |
| 12/14/59 | 79 | 1 | 1 | Flight Control | Control failure, Missile stability lost | N |

**Vehicle Name:** Thor
**Data Collection from:** 57 to 83
**Total Launch Number:** 369
**Total Failure Number:** 66

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 02/04/60 | 83 | 3 | 1 | Electrical | Failure of the fuel injector pressure switches or a short around them | N |
| 02/19/60 | 86 | 2 | 1 | Guidance | Autopilot component failure | N |
| 06/29/60 | 94 | 7 | 2 | Guidance | 2nd stage attitude instability | N |
| 08/18/60 | 97 | 2 | 1 | Propulsion | Failure of the first stage hydraulic system | Y |
| 10/26/60 | 101 | 3 | 2 | Separation | 2nd stage failed to separate | N |
| 11/30/60 | 103 | 1 | 1 | Electrical | Main engine shutdown from a premature MECO signal | N |
| 03/30/61 | 111 | 7 | 3 | Propulsion | A hydraulic system failure resulted in lose of attitute control | Y |
| 06/08/61 | 113 | 1 | 3 | Propulsion | Fuel line leak, Engine failed to provide thrust | Y |
| 07/21/61 | 118 | 4 | 1 | Flight Control | Control system instability | N |
| 08/03/61 | 119 | 0 | 2 | Flight Control | A failure occurred in the hydraulic system which provides the power for engine gimballing | N |
| 10/23/61 | 125 | 5 | 1 | Propulsion | Hydraulic failure and a failure in the engine actuating system | Y |
| 11/05/61 | 126 | 0 | 3 | Guidance | Apogee was higher than predicted as a result of excess velocity | N |
| 01/13/62 | 131 | 4 | 2 | Electrical | Blew a fuse in the line to the gyro guidance packages | N |
| 01/24/62 | 133 | 1 | 2 | Propulsion | 2nd stage misfired, An acutator lug on the 2nd stage thrust chamber was broken | Y |
| 02/21/62 | 134 | 0 | 1 | Propulsion | The fuel vent valve stuck open during first burn | Y |

**Vehicle Name:** Thor
**Data Collection from:** 57 to 83
**Total Launch Number:** 369
**Total Failure Number:** 66

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 03/19/62 | 136 | 1 | 1 | Guidance | Pitch HIG gyro malfunction | N |
| 05/10/62 | 140 | 3 | 1 | Electrical | Failure of the 1st and 2nd stages to separate which was caused by 1st stage electrical malfunction | N |
| 06/20/62 | 147 | 6 | 1 | Propulsion | High temps weakened the load-carrying capabilit of the Thor engine section | N |
| 07/25/62 | 153 | 5 | 1 | Propulsion | The main oxidizer valve only partially opened | N |
| 10/15/62 | 162 | 8 | 1 | Propulsion | The actuator potentionmeter voltage show a continuing loss of power | Y |
| 02/28/63 | 174 | 11 | 0 | Propulsion | Solid motor failure | Y |
| 03/18/63 | 175 | 0 | 2 | Electrical | Electrical short circuit in the safe-arm junction box | N |
| 04/26/63 | 177 | 1 | 3 | Guidance | Failure in horizon sensors | N |
| 06/12/63 | 179 | 1 | 1 | Propulsion | During 1st engine operation a power short condition developed, igniters were set off by radiated heat from the nozzle | Y |
| 11/09/63 | 191 | 11 | 1 | Propulsion | overheating of the boattail section | Y |
| 11/10/63 | 192 | 0 | 1 | Flight Control | Unstable and premature termination of powered flight | N |
| 03/24/64 | 203 | 10 | 2 | Electrical | Electrical short circuit, loss of guidance and control | N |
| 04/21/64 | 204 | 0 | UK | Flight Control | Failure of flight control | N |
| 04/27/64 | 206 | 1 | UK | UK | UK | UK |
| 05/28/64 | 207 | 0 | UK | UK | UK | UK |

**Vehicle Name:** Thor
**Data Collection from:** 57 to 83
**Total Launch Number:** 369
**Total Failure Number:** 66

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 09/02/65 | 250 | 42 | UK | Guidance | Guidance failure, destroyed by RSO | N |
| 01/06/66 | 260 | 9 | 2 | UK | Failed to orbit | UK |
| 05/03/66 | 269 | 8 | 2 | Propulsion | Fire in thrust section due to leakages | Y |
| 05/18/68 | 301 | 31 | 1 | Guidance | Gyro failure, Booster guidance malfunction | N |
| 02/17/71 | 335 | 33 | 1 | Propulsion | Exploded after 40 sec. | UK |
| 02/18/76 | 354 | 18 | UK | UK | UK | UK |
| | | | | | | |
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| | | | | | | |

**Vehicle Name:** Delta
**Data Collection from:** 60 to 87
**Total Launch Number:** 181
**Total Failure Number:** 12

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 05/13/60 | 1 | 0 | 2 | Flight Control | 2nd stage attitude control malfunction, No 3rd stage ignition | N |
| 03/19/64 | 24 | 22 | 3 | Propulsion | Loss of 3rd stage halfway thru burn | Y |
| 08/25/65 | 33 | 8 | 3 | Propulsion | 3rd stage ignition before separation, Did not achieve orbit | N |
| 09/18/68 | 59 | 25 | 1 | Guidance | 1st stage control system (rate gyro) | N |
| 07/25/69 | 71 | 11 | 3 | Propulsion | 3rd stage (AKM) thrust dropped during burn possibly nozzle blown off | Y |
| 08/27/69 | 73 | 1 | 1 | Propulsion | 1st stage hydraulic system failure | Y |
| 10/21/71 | 86 | 12 | 2 | Flight Control | 2nd stage control gas oxidizer vent valve failure, leak | N |
| 07/16/73 | 96 | 9 | 2 | Propulsion | 2nd stage hydraulic system pump motor failure | Y |
| 01/19/74 | 100 | 3 | 2 | Flight Control | 2nd stage electronics failure | N |
| 04/20/77 | 130 | 29 | 2 | Separation | Clamp band released early | N |
| 09/13/77 | 134 | 3 | 0 | Propulsion | SRM (Castor IV) burn-through | Y |
| 05/03/86 | 178 | 43 | 1 | Electrical | 1st stage electrical short in relay box (main engine shutdown) | N |
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**Vehicle Name:** Titan I
**Data Collection from:** 59 to 65
**Total Launch Number:** 68
**Total Failure Number:** 24

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 08/14/59 | 5 | 4 | 1 | Structure | Vibration fired holddown bolts: 1B1E pulled causing shutdown | N |
| 12/12/59 | 6 | 0 | 1 | Propulsion | Failure on pad: destruct system | UK |
| 02/05/60 | 8 | 1 | 1 | Structure | Failure at T+43 sec. | N |
| 03/08/60 | 10 | 1 | UK | UK | UK | UK |
| 04/08/60 | 12 | 1 | UK | UK | UK | UK |
| 07/01/60 | 18 | 5 | 1 | Propulsion | Failure at stage I hydraulics | Y |
| 07/28/60 | 19 | 0 | 1 | Propulsion | Stage I premature shutdown | UK |
| 08/10/60 | 20 | 0 | UK | UK | UK | UK |
| 09/29/60 | 23 | 2 | UK | UK | UK | UK |
| 12/03/60 | 26 | 2 | 1 | UK | Vehicle destroyed | UK |
| 12/20/60 | 27 | 0 | 2 | Propulsion | No stage II ignition | UK |
| 01/20/61 | 28 | 0 | 2 | Propulsion | No stage II ignition | UK |
| 03/02/61 | 31 | 2 | 2 | UK | Premature stage II shutdown | UK |
| 03/31/61 | 33 | 1 | 1 | UK | Premature stage I shutdown | UK |
| 06/23/61 | 36 | 2 | 2 | UK | Premature stage II shutdown | UK |

**Vehicle Name:** Titan I
**Data Collection from:** 59 to 65
**Total Launch Number:** 68
**Total Failure Number:** 24

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 12/15/61 | 49 | 12 | 2 | Propulsion | No stage II ignition | UK |
| 01/20/62 | 50 | 0 | 2 | Propulsion | No stage II ignition | UK |
| 02/23/62 | 52 | 1 | 2 | Propulsion | No stage II ignition | UK |
| 05/01/63 | 60 | 7 | 1 | Propulsion | Failure at liftoff | UK |
| 07/16/63 | 61 | 0 | 2 | Propulsion | No stage II ignition | UK |
| 08/30/63 | 63 | 1 | 1 | Propulsion | Gas generator shutdown | Y |
| 12/08/64 | 66 | 2 | 2 | UK | Stage II prel. shutdown | UK |
| 01/14/65 | 67 | 0 | 2 | Propulsion | No stage II ignition | UK |
| 03/05/65 | 68 | 0 | 1 | Propulsion | Propellant depletion | Y |
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**Vehicle Name:** Titan II
**Data Collection from:** 62 to 76
**Total Launch Number:** 94
**Total Failure Number:** 16

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 06/07/62 | 2 | 1 | 2 | Propulsion | Stage II gas generator oxidizer injection blocked | Y |
| 07/25/62 | 4 | 1 | 2 | Propulsion | Stage II fuel pump leak downstream of TCV failure due to combustion instability | Y |
| 12/06/62 | 8 | 3 | 2 | Propulsion | Stage II oxidizer bootstrap line failure | Y |
| 01/10/63 | 10 | 1 | 2 | Propulsion | Gas generator oxidizer injector blocked | Y |
| 02/16/63 | 13 | 2 | 1 | Separation | Umbilicals failed to disconnect properly | N |
| 04/19/63 | 15 | 1 | 2 | Propulsion | Bootstrap premature shutdown | Y |
| 05/09/63 | 17 | 1 | 2 | Propulsion | OX leak, Premature shutdown of stage II 10% loss of stage II oxidizer during S II flight | N |
| 05/29/63 | 20 | 2 | 1 | Propulsion | Subassembly 1 thrust chamber fuel valve leak occurred at engine ignition | Y |
| 06/20/63 | 21 | 0 | 2 | Propulsion | Gas generator oxidizer injector clogging | Y |
| 04/30/65 | 45 | 23 | 1 | Propulsion | Subassembly / shutdown abruptly and vehicle flight continued erratically, Turbopump failure | Y |
| 06/14/65 | 48 | 2 | 1 | Flight Control | Loss of vernier nozzle | N |
| 09/21/65 | 54 | 5 | 2 | Electrical | Premature shutdown of stage II, bad connector coupled with a surge in the AOS power | N |
| 11/30/65 | 57 | 2 | 1 | Propulsion | Fuel leak, possibly at cross-over manifold with resultant thrust vectoring | Y |
| 12/22/65 | 60 | 2 | 2 | Human (Guidance) | Control of record stage lost following staging Probably due to technician reading wrong scale | N |
| 05/24/66 | 67 | 6 | 1 | Separation | No r/v Separation | N |

**Vehicle Name:** Titan II
**Data Collection from:** 62 to 76
**Total Launch Number:** 94
**Total Failure Number:** 16

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 04/12/67 | 69 | 1 | 2 | Flight Control | Stage II yaw rate gyro | N |
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**Vehicle Name:** Titan III
**Data Collection from:** 64 to 87
**Total Launch Number:** 137
**Total Failure Number:** 11

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 09/01/64 | 1 | 0 | 3 | Propulsion | Premature transtage cutoff, Pressure system failure | Y |
| 10/15/65 | 6 | 4 | 3 | Propulsion | Propellant freezing in stage III engine bi-prop valve engine failed to shutdown | Y |
| 12/21/65 | 7 | 0 | 3 | Flight Control | ACS engines failed to shutdown after vernier burn loss of attitude control | N |
| 08/26/66 | 10 | 3 | 0 | Structure | P/L fairing failure during SRM flight | Y |
| 04/26/67 | 16 | 5 | 2 | Propulsion | Stage II engine thrust dropped to 1/2 nominal gross contamination on Martin side of interface | Y |
| 11/06/70 | 48 | 31 | 3 | Guidance | IGS-IMU failure, The electronic suspension of the IMU shorted out | N |
| 02/11/74 | 75 | 26 | 3 | Propulsion | Centaur stage failed to start after separation, failure of $LO_2$ boost pump | N |
| 05/20/75 | 85 | 9 | 3 | Guidance | IMU failed, Internally shorted transistor | N |
| 09/15/76 | 99 | 13 | 2 | Propulsion | Engine failed to shutdown on command burned to completion, hard contaminant in fuel valve | Y |
| 09/05/77 | 106 | 6 | 2 | Propulsion | Low velocity at stage II shutdown | Y |
| 03/25/78 | 110 | 3 | 2 | Propulsion | Turbine drive hydraulic pump failure after ignition | Y |
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**Vehicle Name:** Titan 34D
**Data Collection from:** 82 to 87
**Total Launch Number:** 11
**Total Failure Number:** 2

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 08/28/85 | 8 | 7 | 1 | Propulsion | Stage I engine shutdown prematurely-massive leak shortly after ignition | Y |
| 04/18/86 | 9 | 0 | 0 | Propulsion | Insulation/case debond vehicle disintegrated at T+8.764 the first explosive flash was noted | Y |

**Vehicle Name:** Atlas A
**Data Collection from:** 57 to 58
**Total Launch Number:** 8
**Total Failure Number:** 5

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 06/11/57 | 1 | 0 | | Structure | | |
| 09/25/57 | 2 | 0 | | Structure | | |
| 02/07/58 | 5 | 2 | | Flight Control | | |
| 02/20/58 | 6 | 0 | | Flight Control | | |
| 04/05/58 | 7 | 0 | | Propulsion | | |
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**Vehicle Name:** Atlas B
**Data Collection from:** 58 to 59
**Total Launch Number:** 9
**Total Failure Number:** 4

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 07/19/58 | 1 | 0 | | Flight Control | | |
| 09/18/58 | 5 | 3 | | Propulsion | | |
| 11/17/58 | 6 | 0 | | Propulsion | | |
| 01/15/58 | 8 | 1 | | Propulsion | | |
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**Vehicle Name:** Atlas C
**Data Collection from:** 58 to 59
**Total Launch Number:** 6
**Total Failure Number:** 3

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 01/27/59 | 2 | 1 | | Guidance | | |
| 02/20/59 | 3 | 0 | | Propulsion | | |
| 03/18/59 | 4 | 0 | | Propulsion | | |
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**Vehicle Name:** Atlas D
**Data Collection from:** 59 to 67
**Total Launch Number:** 197
**Total Failure Number:** 42

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 04/14/59 | 1 | 0 | | Propulsion | | |
| 05/18/59 | 2 | 0 | | Propulsion | | |
| 06/06/59 | 3 | 0 | | Propulsion | | |
| 09/09/59 | 6 | 2 | 1/2 | Electrical | Electrical signal to initiate separation did not reach the pyrotechnic cartridges | N |
| 09/16/59 | 8 | 1 | | Propulsion | Hydraulic failure | |
| 01/26/60 | 19 | 10 | | Guidance | | |
| 03/10/60 | 23 | 3 | | Propulsion | | |
| 04/07/60 | 24 | 0 | | Propulsion | | |
| 05/06/60 | 26 | 1 | | Flight Control | | |
| 06/22/60 | 30 | 3 | | Electrical | | |
| 07/02/60 | 32 | 1 | | Electrical | | |
| 07/22/60 | 33 | 0 | | Flight Control | | |
| 07/29/60 | 34 | 0 | | Structure | Static or dynamic loads, higer than could be predected, rupture of LOX tank | N |
| 09/12/60 | 37 | 2 | | Propulsion | | |
| 09/29/60 | 41 | 0 | | Electrical | | |

**Vehicle Name:** Atlas D
**Data Collection from:** 59 to 67
**Total Launch Number:** 197
**Total Failure Number:** 42

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 10/12/60 | 43 | 1 | | Propulsion | | |
| 12/15/60 | 47 | 3 | 1 | Structure | Rupture in the missile LOX tank | Y |
| 04/25/61 | 52 | 4 | 1/2 | Flight Control | Unsatisfactory due to a failure in the flight control system | N |
| 09/09/61 | 57 | 4 | 1/2 | Electrical | Failure of the ground power umbilical to eject normally at liftoff | N |
| 10/21/61 | 59 | 1 | 1/2 | Guidance | roll control was lost | N |
| 11/22/61 | 61 | 1 | 1/2 | Flight Control | Booster pitch control lost | N |
| 12/22/61 | 65 | 3 | 2 | Flight Control | Sustainer engine failed to cutoff | N |
| 01/26/62 | 68 | 2 | 1/2 | Guidance | Failure of Mod III G Guidance system | N |
| 02/21/62 | 71 | 2 | | Propulsion | | |
| 04/09/62 | 74 | 2 | 2 | Electrical | Electrical failure, excess altitude and under-velocity condition | N |
| 07/22/62 | 87 | 12 | 2 | Guidance | Failure of engine burning time | N |
| 10/02/62 | 92 | 4 | | Electrical | | |
| 12/17/62 | 98 | 5 | 1 | Propulsion | Thrust chamber oscillation | Y |
| 01/25/63 | 100 | 1 | | Structure | | |
| 03/09/63 | 104 | 3 | | Flight Control | | |

**Vehicle Name:** Atlas D
**Data Collection from:** 59 to 67
**Total Launch Number:** 197
**Total Failure Number:** 42

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 03/15/63 | 106 | 1 | | Propulsion | Hydraulic failure | |
| 03/16/63 | 107 | 0 | | Flight Control | | |
| 06/12/63 | 111 | 3 | 1/2 | Propulsion | Booster hydraulic accumulater failure, Exploded just after launch | Y |
| 09/06/63 | 117 | 5 | | Propulsion | Hydraulic failure | |
| 09/11/63 | 118 | 0 | | Propulsion | | |
| 10/07/63 | 119 | 0 | | Propulsion | | |
| 11/13/63 | 123 | 3 | | Propulsion | Hydraulic failure | |
| 01/21/65 | 149 | 25 | | Propulsion | Injection failure, no separation | Y |
| 03/02/65 | 153 | 3 | 1/2 | Propulsion | Stage failed due to loss of thrust | Y |
| 05/27/65 | 159 | 5 | 1/2 | Propulsion | Booster exploded | Y |
| 03/04/66 | 175 | 15 | 1/2 | Flight Control | Failure of sustainer low pressure hydraulic system at booster jettison | N |
| 05/03/66 | 179 | 3 | UK | UK | UK | UK |
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**Vehicle Name:** Atlas E
**Data Collection from:** 60 to 88
**Total Launch Number:** 49
**Total Failure Number:** 18

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 10/11/60 | 1 | 0 | 1/2 | Guidance | Nitrogen control-gas was broken off, causing control-gas depletion | N |
| 11/29/60 | 2 | 0 | 1 | Propulsion | Loss of sustainer engine hydraulic pressure | Y |
| 01/24/61 | 3 | 0 | 1 | Flight Control | Lost vehicle stability | N |
| 03/13/61 | 5 | 1 | 1 | Flight Control | Premature shutdown of the sustainer engine due to fuel depletion | N |
| 03/24/61 | 6 | 0 | 1/2 | Flight Control | Control bottle helium was depleted during boost phase and the booster package was not jettisoned | N |
| 06/07/61 | 9 | 2 | 1/2 | Propulsion | Combustion instability in B1 thrust chamber | Y |
| 06/22/61 | 10 | 0 | 1/2 | Flight Control | Excessive pitchover rate during boost phase | N |
| 09/08/61 | 13 | 2 | 1 | Propulsion | Sustainer engine shutdown shortly after jettison of the booster section | Y |
| 11/10/61 | 16 | 2 | 1 | Propulsion | Sustainer engine shutdown during main stage transition | Y |
| 02/28/62 | 20 | 3 | UK | Structure | UK | UK |
| 07/13/62 | 21 | 0 | 1 | Propulsion | LOX leak during flight, failure of slow-closing propellant valve | Y |
| 12/18/62 | 22 | 0 | 1/2 | Propulsion | Booster engine shutdown due to loss of lube oil | Y |
| 07/26/63 | 26 | 3 | 1 | Electrical | Spurious voltage transients on range safey cutoff circuitry | N |
| 09/25/63 | 29 | 2 | 1 | Propulsion | Sustainer hydraulic system failed at staging | Y |
| 02/12/64 | 30 | 0 | 1 | Guidance | Guidance failure in premature engine cutoffs | N |

**Vehicle Name:** Atlas E
**Data Collection from:** 60 to 88
**Total Launch Number:** 49
**Total Failure Number:** 18

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 08/27/64 | 32 | 1 | UK | Guidance | Radial impact error BB NM short, GD/A did not perform an analysis | N |
| 12/08/80 | 36 | 3 | 1/2 | Propulsion | Booster engine nol 2 shutdown prematurely, due to loss of oil | Y |
| 12/18/81 | 37 | 0 | 1/2 | Propulsion | Propulsion B1 GG burn through | Y |
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**Vehicle Name:** Atlas F
**Data Collection from:** 61 to 81
**Total Launch Number:** 96
**Total Failure Number:** 17

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 12/12/61 | 3 | 2 | 1 | Guidance | The ARMA guidance system computer malfunctioned. Engine cutoff 4 sec early | N |
| 12/20/61 | 4 | 0 | 1 | Propulsion | Loss of sustainer hydraulic pump iniet pressure | Y |
| 04/09/62 | 5 | 0 | 1 | Propulsion | The sustainer lox turbopump was destroyed by an internal overpressure | Y |
| 08/10/62 | 7 | 1 | 1 | Flight Control | Missile failed to roll to the planned target azimuth | N |
| 11/14/62 | 12 | 4 | 1 | Guidance | Guidance computer malfunctioned | N |
| 03/23/63 | 17 | 4 | UK | UK | Missle self-destructed at 91 sec. | UK |
| 10/03/63 | 19 | 1 | 1/2 | Propulsion | B1 Main fuel valve failed to open | Y |
| 10/28/63 | 20 | 0 | 1 | Propulsion | Sustainer hydraulic return system failed | Y |
| 04/03/64 | 23 | 2 | 1/2 | Propulsion | Thrust imbalance due to B1 main fuel valve sticking | Y |
| 08/08/66 | 29 | 5 | 1/2 | Propulsion | Abnormal operation of B2 engine caused high fuel and iow LOX usage, partial blockage of the B2 LOX high pressure system | Y |
| 10/11/66 | 30 | 0 | 1/2 | Propulsion | Fuel starvation of B1 engine due to malfunction of B1 engine fuel prevalve | Y |
| 10/27/67 | 39 | 8 | 1/2 | Propulsion | Loss of vehicle stability caused by small leak in booster hydraulic high pressure system | Y |
| 05/03/68 | 45 | 5 | 1 | Flight Control | Divergent oscillations of booster pitch control | N |
| 11/06/68 | 52 | 6 | 1 | Propulsion | Vernier engine hydraulic pressure lost after SECO | Y |
| 10/10/69 | 58 | 5 | 1 | Propulsion | Sustainer and vernier engines shutdown prematurely | Y |

**Vehicle Name:** Atlas F
**Data Collection from:** 61 to 81
**Total Launch Number:** 96
**Total Failure Number:** 17

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 04/12/75 | 80 | 21 | 1 | Propulsion | Damaged thrust section allowed overheating and premature shutdown of the sustainer and vernier engines | Y |
| 05/29/80 | 95 | 14 | 1/2 | Propulsion | B1 engine performance was 79% of nominal and injection time was late | Y |
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**Vehicle Name:** Atlas SLV
**Data Collection from:** 67 to 83
**Total Launch Number:** 73
**Total Failure Number:** 4

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 11/30/70 | 26 | 25 | 2 | Separation | Nose fairing failure to jettison | N |
| 12/04/71 | 30 | 3 | 1 | Flight Control | Lost attitude control E pack | N |
| 02/20/75 | 42 | 11 | 1 | Electrical | Electrical disconnect failure during Atlas boost separation | N |
| 09/29/77 | 52 | 9 | 1/2 | Propulsion | Hot gas leak in the booster gas generator | Y |
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**Vehicle Name:** Atlas G
**Data Collection from:** 84 to 87
**Total Launch Number:** 6
**Total Failure Number:** 1

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 03/26/87 | 6 | 5 | | Other | Lightning struck vehicle | N |
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Vehicle Name: Atlas H
Data Collection from: 83 to 87
Total Launch Number: 5
Total Failure Number: 0

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
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**Vehicle Name:** Atlas/Centaur
**Data Collection from:** 62 to 87
**Total Launch Number:** 67
**Total Failure Number:** 11

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 05/08/62 | 1 | 0 | 2 | Structure | Centaur upper stage structure failure | N |
| 06/30/64 | 3 | 1 | 2 | Propulsion | Centaur hydraulic failure, Loss of $C_2$ hydraulic power | N |
| 03/02/65 | 5 | 1 | 1/2 | Propulsion | Loss of Atlas thrust during liftoff, due to fuel starvation of booster engines stemming from closure of fuel prevelue | Y |
| 04/07/66 | 7 | 1 | 2 | Propulsion | Centaur restart sequence failure, engine ignition occurred but not sustained due to fuel deplation | N |
| 08/10/68 | 16 | 8 | 2 | Propulsion | Failure of boost pump $H_2O_2$ supply system centaur didn't achieve its second main engine start | N |
| 11/30/70 | 21 | 4 | 1 | Separation | Nose fairing failed to jettison properly | N |
| 05/08/71 | 23 | 1 | 2 | Flight Control | Centaur pitch control lost | N |
| 02/20/75 | 34 | 10 | 1 | Electrical | Atlas booster section electrical disconnect failed during booster jettison | N |
| 09/29/77 | 42 | 7 | 1/2 | Propulsion | Atlas booster engine hot gas leak failed mission | Y |
| 06/09/84 | 62 | 19 | 2 | Propulsion | Failure occurred at A/C Separation a liquid oxygen tank crack | N |
| 03/26/87 | 67 | 4 | --- | other | Lightning strike failed mission | N |
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**Vehicle Name:** Jupiter
**Data Collection from:** 58 to 58
**Total Launch Number:** 6
**Total Failure Number:** 3

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 03/05/58 | 2 | 1 | 4 | Propulsion | 4th stage failed to ignite | Y |
| 08/28/58 | 5 | 2 | 2 | Separation | Booster burned into remaining stage upper stage fired in wrong direction | N |
| 10/23/58 | 6 | 0 | 2 | Separation | 2nd stage failed to fire premature separation | N |
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**Vehicle Name:** Juno
**Data Collection from:** 58 to 61
**Total Launch Number:** 10
**Total Failure Number:** 5

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 07/16/59 | 3 | 2 | UK | Guidance | Guidance failed, destroyed by RSO | N |
| 08/14/59 | 4 | 0 | 1 | Propulsion | Booster fuel depletion | Y |
| 03/23/60 | 6 | 1 | 3 | UK | Ignition malfunction | UK |
| 02/24/61 | 8 | 1 | 2 | UK | 2nd stage malfunction | UK |
| 05/24/61 | 10 | 1 | 2 | UK | 2nd stage failed to ignite | UK |
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**Vehicle Name:** Saturn I
**Data Collection from:** 62 to 65
**Total Launch Number:** 10
**Total Failure Number:** 0

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
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**Vehicle Name:** Saturn IB
**Data Collection from:** 66 to 75
**Total Launch Number:** 9
**Total Failure Number:** 0

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
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**Vehicle Name:** Saturn V
**Data Collection from:** 67 to 73
**Total Launch Number:** 13
**Total Failure Number:** 1

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 04/04/68 | 2 | 1 | 2<br>3 | Propulsion | Second stage engine malfunction<br>Third stage failure to restart | Y |
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**Vehicle Name:** Vanguard
**Data Collection from:** 57 to 59
**Total Launch Number:** 11
**Total Failure Number:** 8

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 12/06/57 | 1 | 0 | 1 | Propulsion | First stage lost thrust, exploded after 2 second | Y |
| 02/05/58 | 2 | 0 | 1 | Flight Control | First stage control system malfunction after 57 sec | N |
| 04/28/58 | 4 | 1 | 2 | Propulsion | Bad 2nd stage shutdown preventing 3rd stage firing | Y |
| 05/27/58 | 5 | 0 | 3 | Flight Control | Improper 3rd stage trajectory loss of attitude control | N |
| 06/26/58 | 6 | 0 | 2 | UK | Early 2nd stage shutdown prevented 3rd stage firing | UK |
| 09/26/58 | 7 | 0 | 2 | UK | Below minimum 2nd stage performance prevented orbit | UK |
| 04/14/59 | 9 | 1 | 2 | Guidance | Loss of 2nd stage pitch control | N |
| 06/22/59 | 10 | 0 | 2 | Propulsion | Low tank pressures after 2nd stage ignition caused instability | Y |
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**Vehicle Name:** Scout
**Data Collection from:** 60 to 88
**Total Launch Number:** 110
**Total Failure Number:** 14

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 12/04/60 | 3 | 2 | 2 | Electrical | Failed to ignite: Caused by wire break or disconnected power input | N |
| 06/30/61 | 5 | 1 | 3 | Propulsion | Improper venting causing ignition leads to be severed | Y |
| 08/25/61 | 6 | 0 | 4 | Separation | Diaphragm separation system failure | N |
| 11/01/61 | 8 | 1 | 1 | Guidance | Guidance failure destroyed by RSO after 30 sec | N |
| 04/26/62 | 11 | 2 | 3 | Guidance | Control was lost due to $H_2O_2$ not being available | N |
| 05/23/62 | 12 | 0 | 2 | UK | 2nd stage shock input all three axes 0.29 sec after ignition | UK |
| 04/05/63 | 18 | 5 | 3 | Flight Control | 3rd stage reaction control system failure | N |
| 04/26/63 | 19 | 0 | 3 | Electrical | short circuit in the destruct system, attitude control was lost | N |
| 07/20/63 | 23 | 3 | 1 | Propulsion | stage I engine nozzle failure | Y |
| 09/27/63 | 24 | 0 | 4 | Flight control | Pitch motor failure, loss of vehicle control | N |
| 06/25/64 | 28 | 3 | 2 | Electrical | Linear shaped destruct charge was ignited by an unplanned electrical input | N |
| 01/31/67 | 51 | 22 | 4 | Propulsion | Motor graphite nozzle insert resulted in rupture of the motor case | Y |
| 05/29/67 | 56 | 4 | 3 | Propulsion | Failure of motor caused by unstable chumber pressure | Y |
| 12/05/75 | 94 | 37 | 3 | Propulsion | 3rd stage nozzle failure | Y |
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**Vehicle Name:** Space Shuttle
**Data Collection from:** 81 to 88
**Total Launch Number:** 26
**Total Failure Number:** 1

| Date | Failure Launch | Success Run | Failure Stage | Failure System | Failure Description | Engine/Motor Failure Y/N |
|---|---|---|---|---|---|---|
| 01/28/86 | 25 | 24 | 0 | Propulsion | Vehicle exploded 73 sec. after launch-SRM O-ring failure | Y |
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